Morphotectonic expression of geological structures in the eastern part of the South East Deccan Volcanic Province (around Nanded, Maharashtra, India)

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Abstract: We geomorphometrically characterize the tectonics near the microseismically active Nanded region, Maharashtra, India. We used the geomorphic indices of active tectonics in 32 sub-basins to evaluate the relationship between tectonics and basin morphology. The area is divided into three different zones (1, 2 and 3). Microseismicity is concentrated along the NW–SE-trending Urvashi Ghat Lineament. The anomalous drainages and lineaments are also confined to the region where microseismicity is associated with thrust. Spatial analysis of the elongation ratio and hypsometric integral of the basins provide valuable information on their distribution and relationship to the structure and tectonics. This study suggests neotectonic control on the evolution of the basins close to Nanded City.

We have focused on the eastern part of the Deccan Volcanic Province (DVP) (Fig. 1a) around the Nanded and Parbhani districts, Maharashtra, India. The Nanded region has been experiencing micro-earthquake activity since November 2006 (Table 1). The seismic data are documented on seismomemeters at the School of Earth Sciences, S.R.T.M. University, Nanded, approximately 8 km south of the Urvashi Ghat Lineament (UG Lineament) and at 1.5 km NE of the UG Lineament. The third one is located 1.4 km NNE to the UG Lineament. Local shocks, some of which were accompanied by subterranean sounds up to 3.1 coda magnitude, were reported during 2006–2013 without any damage, with the epicentre located in the heart of the city of Nanded (Fig. 1b).

Kaplay *et al.* (2013) reported deformation from Nanded that supports micro-earthquakes from the SE Deccan Volcanic Province (SEDVP). These include: (i) brittle fracturing and displacement of pipe amygdules (minor faults); (ii) antiformal folds with associated brittle/brittle–ductile faults dipping towards the east; (iii) ramps with flat planes dipping towards the east; and (iv) ductile shear of basaltic veins. Stream characteristics in reference to anomalous drainage patterns are also studied. We report here new deformation features from the Quaternary deposits in the SEDVP.

Rajaguru & Kale (1985) and Rajaguru *et al.* (1993) studied fluvial systems in the upland areas of the Deccan Trap, from the western coastal area and the Western Ghat. Kale & Shejwalkar (2008) carried out geomorphological analyses in the Western Deccan Basalt Province (Western Ghat). The authors have concluded that ‘during last 1.4 m.y. the geomorphologically stable channels were found prone to Quaternary climatic changes which is evident from the synchronous pattern of depositional events’ (Rajaguru *et al.* 1993, p. 817). Kale & Shejwalkar (2008) concluded that geomorphic indices of active tectonics (GAT) do not help in detecting the subtle imprints of the tectonic activity, even if the DVP has undergone significant uplift in recent times. Tectonics may leave only faint imprints on the present-day landscape (Kale & Shejwalkar 2008).

Geomorphometric characterization of the tectonic properties of a landscape is not straightforward. Geomorphic indices can reveal relationships between basin morphology and tectonics (Keller & Pinter 1996; Burbank & Anderson 2001). This part of the DVP is suitable for such geomorphometric analyses, and to compare basins and fluvial systems (Kaplay *et al.* 2013). Bearing in mind the evidence of faults from the Deccan Trap in the Nanded region, efforts are made in this study to

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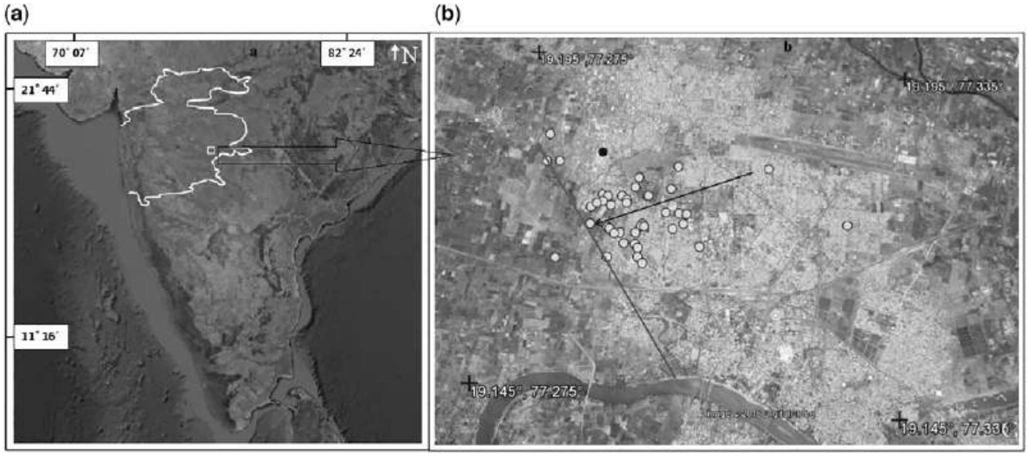

Fig. 1. (**a**) Location map of the study area. (**b**) Map showing the shift in microseismicity towards the west nearer to the UG Lineament (black line). The solid black circle is a site where granite is encountered at a depth of 200 m.

find the tectonic nature of the basins around the Godavari River that cover the districts of Nanded and Parbhani.

Study area

The study area, which covers a stretch of the Godavari River 292.88 km in length, includes 32 sub-basins (Fig. 2). The study area is located along the boundary of the SEDVP (Fig. 1) and is mostly Deccan basalts.

Geology

The region dominantly comprises compact, amygdaloidal and vesicular basalt. The basalt flows have been assigned to the Ajanta Formation, which is the stratigraphic equivalent of the Upper Ratangad Formation of the Wai sub-group of west Maharashtra comprising compound flows (Godbole *et al.* 1996). The compound (pahoehoe) flows are formed by the outpouring of low-viscousity lava through a large number of outlets (Bondre *et al.* 2000, 2004; Duraiswami *et al.* 2003, 2008). Consequently, they are large, irregular and have a greater lateral extent (Duraiswami *et al.* 2001, 2002).

The traps are approximately 200 m thick, greenish-grey and medium grained. They contain typical segregation of circular/lenticular/short banded vesicles. The amygdules are filled with chlorite, calcite, zeolite and chalcedony. The traps contain devitrified glasses and secondary zeolites, and are overlain by 5–15 m-thick alluvium along the Godavari River, which is flowing towards the east and SE. The maximum thickness of the Quaternary deposit on the northern bank of the Godavari River is 42 m in the Nanded district, with a gravel bed at the base above massive (aa) basalt (Tiwari 1999).

The Nanded district is mainly underlain by unclassified crystalline rocks, viz. granites and gneisses, along with pegmatite, ultrabasic dykes and quartz veins of Archaean–Palaeo-proterozoic age, Late Cretaceous–Early Eocene basalts and (sub) recent alluvium (Table 2) (Nanded District Gazetteer 1971; Madhnure 2006, 2014; CGWB 2012). Basaltic rocks occupy most of the places overlying

Table 1. *Details of microseismic events from Nanded, Maharashtra, India*

Sr. No.	YYYYMMDD	HHMMSS.SS	Latitude	Longitude	Depth (km)	Magnitude
1	20071114	152955.13	19° 9.93	77° 19.45	2.9	2
2	20071121	023031.57	19° 10.51	77° 18.58	3.1	1
3	20071214	122705.03	19° 11.45	77° 16.85	2.1	3
4	20101207	112648.54	19°.18 9.67	77°.30 5	1.9	1.9
5	20110302	220023.09	19°.17 4.67	77°.29 9.5	0.8	3.1
6	20111216	135805.57	19°.16 6.33	77°.30 4.83	0	1.6

Sr. No. 1, 2 and 3 after Srinagesh *et al.* (2008); the primary data for 4, 5 and 6 was recorded on a seismometer located in S.R.T.M. University, Nanded, Maharashtra, India.

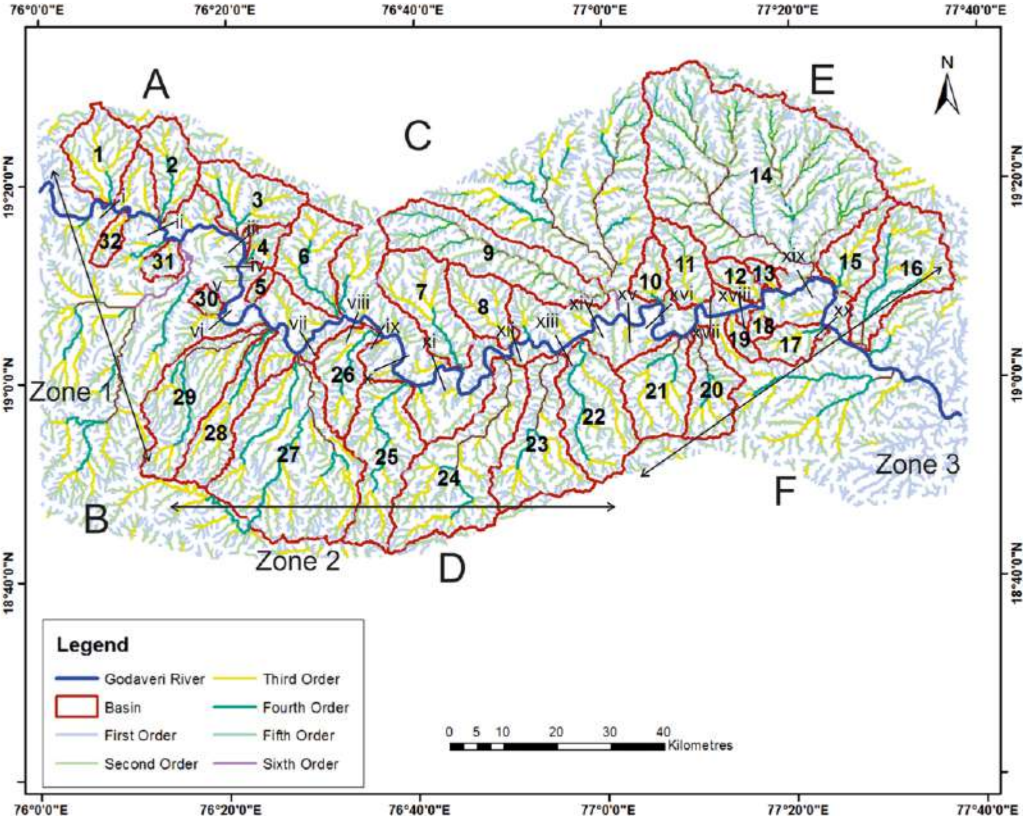

Fig. 2. Drainage map of the 32 sub-basins in the SEDVP area along the Godavari River. The locations of the sub-basins marked as 1–32 in the figure and in Table 1 are: (1) Jamb; (2) Ashti; (3) Zari; (4) Masala; (5) Loni; (6) Vajhur; (7) Indrayani; (8) Khadki (Vajhur); (9) Pingalgad; (10) Khadki; (11) Alegaon; (12) Sugaon; (13) Urvashi Ghat; (14) Asna; (15) Barod; (16) Sita; (17) Kankadi; (18) Dhangarwadi; (19) Bhanagi; (20) Sangvi; (21) Jhod; (22) Dhond; (23) Galati; (24) Macchhali; (25) Borna; (26) Dhamunwadi; (27) Lingi; (28) Gunwara; (29) Sarasvati; (30) Abujwadi; (31) Padmavati; and (32) Waghora. The study area shows sub-basins on the northern and southern sides of the Godavari River. It also shows three different zones (1–3), which are used for the study of spatial analysis. The zones are further classified as the northern side (A, C and E) and the southern side (B, D and F). Numbers i–xx along the Godavari River are the segments for determination of the valley floor width to valley height ratios. Location names are given in Table 5.

granites. The traps are massive, fine-grained, black grey to brown, and are of both 'pahoehoe' and 'aa' types. The pahoehoe type is predominantly vesicular basalt with very thin massive portions. The 'aa' flow of thick massive basalt shows columnar joints and spheroidal weathering, with an upper vesicular

Table 2. *Generalized geological succession in Nanded district*

Stratigraphic units	Rock Formations	Age
Alluvium	Clay mixed with silt, sand and gravel	Recent–sub-Recent
Deccan traps	Black, grey, vesicular amygdaloidal, massive basalt with intertrappean, red/black/green boles	Late Cretaceous–early Eocene
Unconformity		
Unclassified gneisses	Granite, granite gneisses, pink and grey with numerous small bands of hematite–quartzite and epidiorites. Pegmatite and quartz veins as intrusive rocks	Archaean–Palaeoproterozoic

portion brecciated. Secondary porosity reduces with depth, and the groundwater storage and circulation are limited to a depth of 177 m.

The easternmost part of the study area is characterized by structural depression identified here as a fault-line scarp, which is aligned along the microseismically active UG Thrust.

Methodology

We selected 32 sub-basins along the Godavari River for geomorphometric analysis (Fig. 2). Geomorphic indices for active tectonics (GAT) were also determined, which include the basin asymmetry factor, the stream gradient to length ratio, the basin elongation ratio and the hypsometric integral. The area is divided into three zones (Fig. 2): Zone 1 trends NW (the Godavari Zone); Zone 2 trends east; and Zone 3 is delineated based on an approximately east-trending course of the Godavari River, for approximately >3 km, which then takes a sharp turn towards the north following a straight course (L_5) and then turns towards the SE (Singh 2008*b*). Zone 3 is characterized by definite structural characters, which include the orientation of the UG Thrust Lineament and related features such as the Kamtha thrusts.

The spatial distribution of the elongation ratio and the hypsometric integral for all the basins studied, initially gave a definite pattern. While the elongation ratio on the northern side is more than on the southern side, the southern part has lower average hypsometric integral values than the northern part. Then, to find the influence of structures on the basins, the two parameters are compared zone-wise. It shows the influence of structures on basins located on one side of the river, as the elongation ratio on the northern side is more than that on the southern side.

The lineament study was carried out using toposheets and was well supported by Google images, as well as by field checks. Lineaments on the imagery were identified based on recognition elements, such as a sharp contrast in tone and structures. Areas around Urvashi Ghat (Figs 1b & 3) and other lineaments were also studied.

Deformation

Srinagesh *et al.* (2012) identified the UG Lineament in the study area from satellite images from the Geological Survey of India (GSI). They also carried out microseismic studies in the Nanded area and suggested that the microseismicity is related to thrusting along a NW–SE fault that coincides with a local stream that joins the Godavari River south of the city of Nanded.

The surface exposure of this lineament, near Urvashi Ghat, is in the form of a 3–4 m-deep nala (natural drain) joining the Godavari River. We did not observe any deformation on the surface exposure of this lineament as it is covered by alluvium. We studied the slope on both sides. The relief of the eastern side of the lineament dips towards the west. The causative fault has its surface manifestation as a lineament and a spatial distribution of well-located events falls along its trend. This causative fault is a thrust fault dipping 60° towards the west. Note that the dip direction of thrusts (*c.* 5 km east of the UG Lineament: the Kamtha thrusts) located in basalts, reported by Kaplay *et al.* (2013), also dip towards the west, which corroborates with the dip direction of the causative fault reported by Srinagesh *et al.* (2012). Most of Nanded City is located on the hanging wall of this causative fault.

The slope of the lineament's surface expression (Fig. 3) is opposite to the dip direction of the thrust (on the right-hand side of the local stream). Thus, it appears that the reversely dipping surface exposure of the UG Lineament is a fault-line scarp with alluvium exposed along it and with no exposures of basalt. The causative fault matches with the lineament (L_6) on the surface. Microseismicity is associated with this UG Lineament and is mostly confined to the eastern side of this lineament with occasional microseismicity on the western side (Fig. 1b).

We studied the western side of UG Lineament. The Quaternary deposits are observed along the junction of two lineaments (L_4 and L_5), which lies on the SW side of the UG Lineament (Fig. 4a). These Quaternary deposits are locally faulted (Fig. 5a). The layer of pebbly gravel bed mixed with sand tapers towards the west and with deformation in the middle layer, with no extension of faults in the other layers (see examples in Mukherjee 2013, 2014*a*, *b*, 2015 from different terrains). The fault on the eastern side shows an offset of approximately 15 cm, whereas on the western side it is 4 cm. These features illustrate the probable influence of Quaternary neotectonics. Sedimentary structures, such as cross-bedding and current beddings (Fig. 5b), are recognized in the Quaternary deposits along the junction of the two lineaments L_4 and L_5, which lies on the SW side of the UG Lineament (Fig. 4).

Another interesting feature found in the field in the Vishnupuri area of the Nanded district is the formation of kink band in the cross-lamination (Fig. 5b). The cross-lamination is at approximately 28° to the horizontal surface. The kink in the cross-lamination may be due to the ductile deformation of the Quaternary neotectonics. The deformation in this sedimentary rock is observed over an area of a few metres. Deformed Quaternary deposits (Fig. 5a, b) are observed near lineaments L_4 and L_5 (Figs 4a & 6b). A normal fault is reported near Nanded

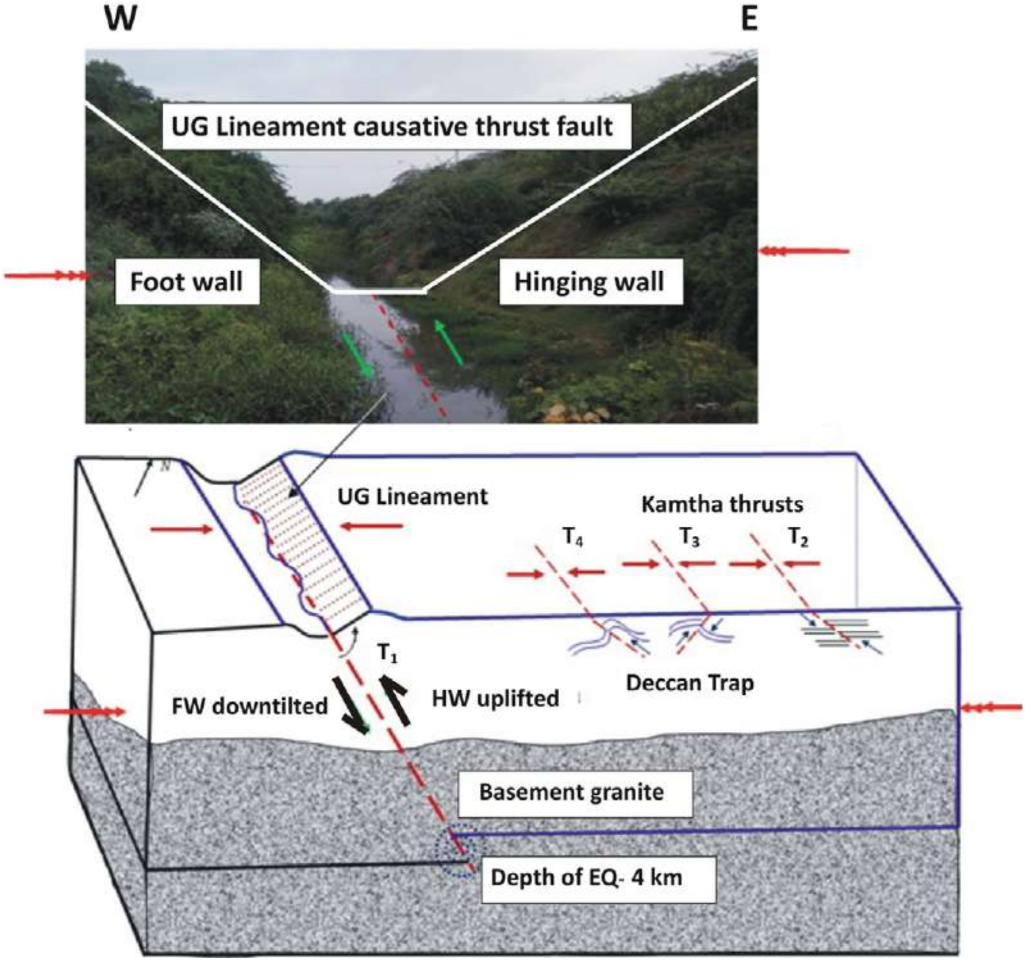

Fig. 3. The Urvashi Ghat Lineament with a slope opposite to the dip of Thrust T1 (causative fault). Cartoon (not to scale) shows the fault-line scarp. T2, T3 and T4 are the thrusts from the Kamtha area (sub-basin 9). T1 is the thrust reported by Srinagesh *et al.* (2012), and T2, T3 and T4 are those from Kaplay *et al.* (2013).

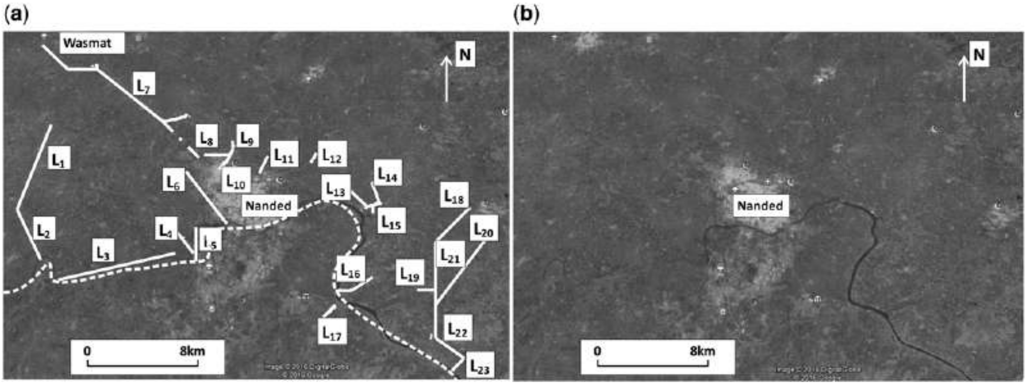

Fig. 4. (**a**) Lineaments in the study area. (**b**) Uninterpreted image.

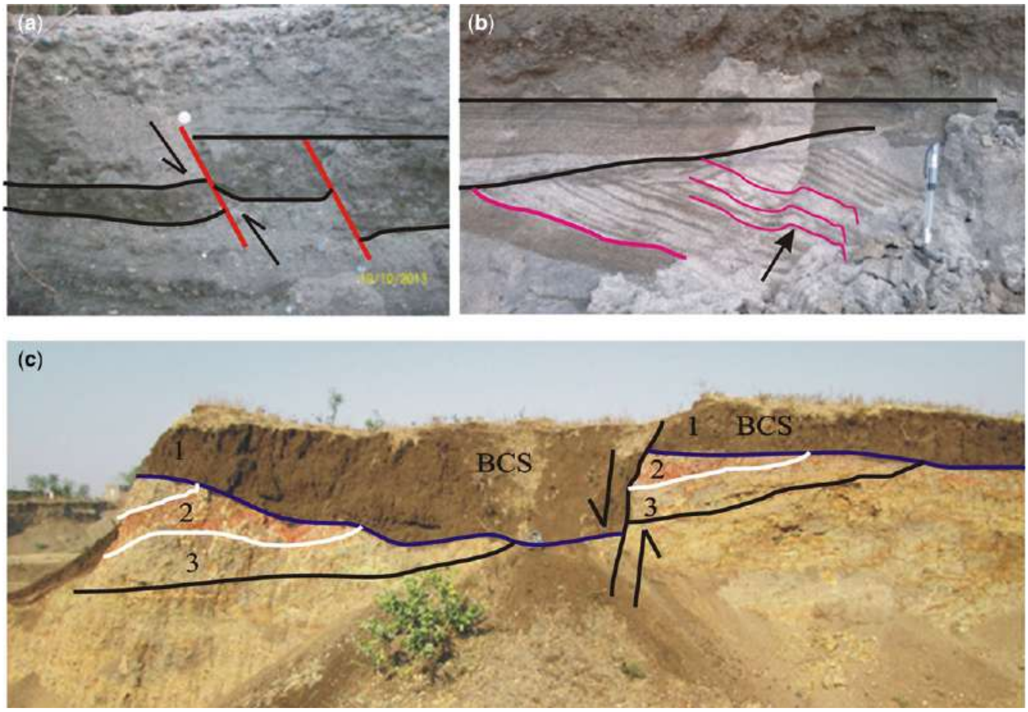

Fig. 5. (**a**) Quaternary deposits near Vishnupuri showing deformation in a pebbly gravel bed mixed with sand. A coin with a diameter of 2.5 cm is used for scale. (**b**) Ductile deformation in a sandy silt deposit showing a kinkband in cross-bedding at Vishnupuri in the Nanded district. (**c**) High-angle 'normal fault' with a throw of 2.21 m. 1, black cotton soil (BCS); 2, red bole bed, 3, greenish tachylitic (bole) basalt layer.

Airport. Here, the red bole basalt layer is displaced by up to 2.21 m (Fig. 5c). The red bole layer is followed by a green bole basalt layer, which is also deformed. The fault plane dips 78° towards the south. However, the fault could not be traced as it is covered with black cotton soil.

Geomorphic indices of active tectonics

The general morphometric attributes of the 32 selected drainage sub-basins along the mid reaches of Godavari River in the Parbhani and Nanded districts (Fig. 2) were determined, including the basin area, the total length of streams, the highest stream order, the length of the trunk stream, and the maximum, minimum and mean basin elevations (Table 3). The analysis of the geomorphic indices of active tectonics (GAT) of 32 sub-basins was carried out to find out whether the sub-basins are tectonically active. The GAT analysis includes area, the basin elongation ratio, the basin asymmetry factor, hypsometric integral, the stream gradient to length ratio (Table 4) and the valley floor width to valley height ratio (Table 5).

Basin elongation ratio (Re)

The basin elongation ratio (Re) quantitatively describes the planimetric shape of a basin and, thus, represents the degree of maturity of the basin landscape. It is calculated using the formula $\mathrm{Re} = (2\sqrt{A}:\sqrt{\pi})/L$, where A is the area of the basin area and L is the length of the basin (Bull & McFadden 1977; Babar *et al.* 2011; Farooq *et al.* 2015). In the present study, the Re ranges from 0.43 to 0.79. The value of Re, except for the Gunawara (0.43) and Pingalgad (0.46) sub-basins, exceeds 0.50 (Table 4), indicating that the sub-basins are moderately elongated (Schumm 1956; Farooq *et al.* 2015). Singh (2008*a*) and Singh & Jain (2009) found that the larger watersheds (sub-basins) are poorly elongated (high elongation ratio), whereas the smaller watersheds are highly elongate (low elongation ratio).

Basin asymmetry factor (AF)

The influence of tectonics on the drainage pattern is also reflected by the asymmetry of the drainage basins (Molin *et al.* 2004). AF is an

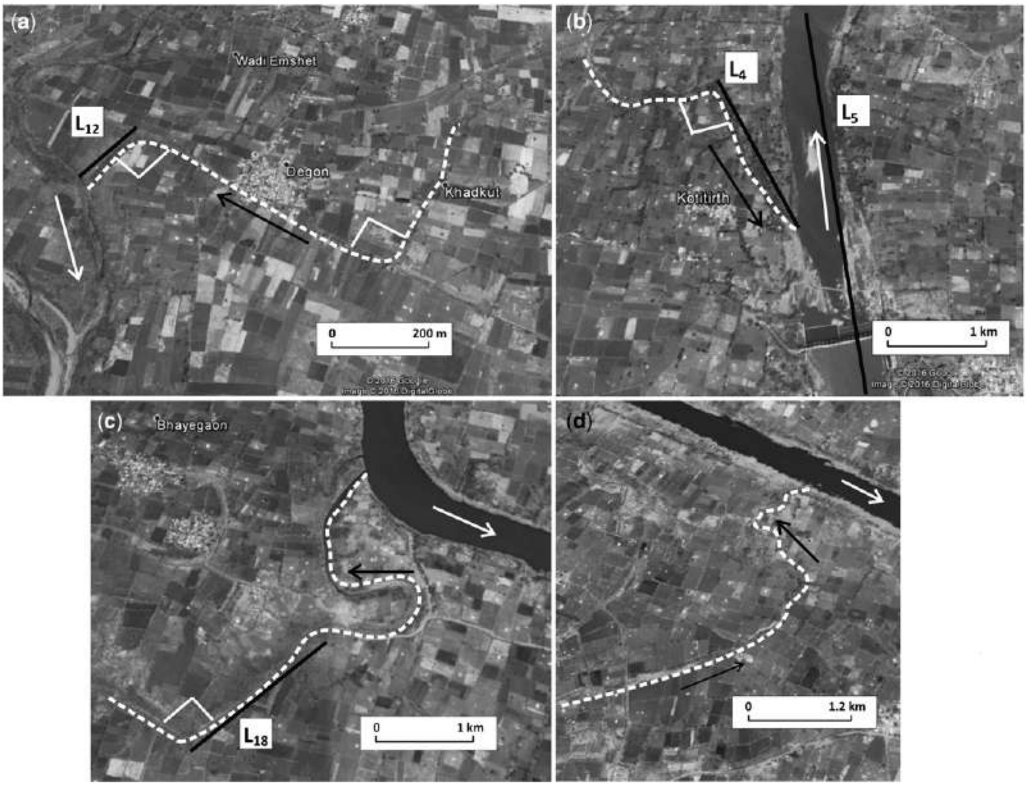

Fig. 6. Off-sequent streams with a sharp knee bend. Hypothetical model of probable hidden structures: (**a**) lineament L_{12} controls the right-angle turn of the stream; (**b**) lineament L_4 controls the right-angle turn of the stream, and L_5 along a major river (Godavari) showing a straight course – the white circle is the location of the deformation in the Quaternary deposits (Fig. 4); (**c**) lineament L_{18} controls the right-angle turn of the stream; and (**d**) the knee bend of the stream and a localized meander before joining the main river. The direction of flow of off-sequent streams is marked with black arrow, and consequent streams (major river) with a white arrow.

areal morphometric variable that deciphers the presence/absence of regional tilt in a basin (Keller & Pinter 1996). It is obtained from the formula AF $= 100(A_r/A_t)$, where A_r is the area of the basin to the right (facing downstream) of the trunk stream and A_t is the total area of the drainage basin (Keller & Pinter 1996). A stream network through a tectonically stable crust and a uniform lithology shows a AF value of approximately 50. The magnitude is diffident in unstable regions (Keller & Pinter 1996). The study area is of uniform lithology and, therefore, AF is expected to be approximately 50. The values of the asymmetry factor are calculated for the 32 sub-basins (Table 4). It is observed that 10 sub-basins (i.e. 31.25% of the sub-basins analysed) were found to have AF values ranging from 45 to 55, we considered these values as the near-normal values; 18.75% of the basins show a value of between 26 and 45; and 21.88% have a value of between 56 and 65. However, the remaining 28.12% of the sub-basins show anomalous values (9.37% show AF < 26 and 18.75% with AF > 66). Out of these 32 sub-basins, 16 are located on the northern side of the Godavari River and the rest in the southern part (Fig. 2). The drainage anomalies are associated with a WNW trend (e.g. the Ashti, Vazur and Khadki sub-basins), whereas the Asna and Sita rivers follow the NW-trending lineament in the microseismically active area of the city of Nanded. The basins of Asna and Sita (sub-basins 14 and 16, respectively) also show anomalous values of AF. Hare & Garner (1985) found that AF can detect tectonic tilt.

Hypsometric analysis

In the present study of the percentage hypsometric integral method, two ratios are computed from contour map measurements. The first one is a/A,

Table 3. *Morphometric attributes of the Godavari River Basin in the Parbhani and Nanded districts of Maharashtra*

Sub-basin No.	Name of sub-basin/ watershed	Highest stream order	Basin area (km^2)	Basin length (km)	Maximum elevation (m)	Minimum elevation (m)	Mean elevation (m)	Length of trunk stream (km)
Sub-basins in the northern part of the Godavari River								
1	Jamb	5	161.45	18.84	481	421	451	19.42
2	Ashti	5	130.09	19.45	879	418	645	27.56
3	Zari	5	171.78	14.96	450	399	425	15.92
4	Masala	4	42.22	11.38	440	397	419	10.24
5	Loni	4	16.65	7.45	424	391	498	7.23
6	Vazur	5	179.99	22.14	441	386	414	28.54
7	Indrayani	5	210.39	26.28	472	380	426	33.18
8	Khadki (Vajhur)	4	127.22	19.02	428	378	403	23.04
9	Pingalgad	4	344.51	45.44	473	369	421	52.13
10	Khadki	4	59.77	12.56	407	368	388	16.97
11	Alegaon	4	114.56	18.29	404	360	382	20.87
12	Sugaon	4	50.60	11.87	398	358	378	15.66
13	Urwashi Ghat	3	20.90	8.39	392	356	374	9.65
14	Asna	6	1185.21	49.45	540	356	448	66.22
15	Barod	5	119.88	20.66	525	355	440	25.02
16	Sita	5	269.08	29.37	526	354	440	39.49
Total			**3204.30**	**335.55**	**7680**	**6046**	**6952**	**411.14**
Mean			**200.27**	**20.97**	**480**	**378**	**435**	**25.70**
Sub-basins in the southern part of the Godavari River								
17	Kankadi	4	68.59	13.16	500	356	428	20.80
18	Dhangarwadi	3	19.87	6.01	473	367	420	8.45
19	Bhanagi	3	28.41	9.80	474	367	421	12.67
20	Sangvi	5	146.49	21.32	486	365	426	25.29
21	Jhod	5	195.47	20.95	490	367	429	26.88
22	Dhond	5	262.27	27.11	515	372	449	31.12
23	Galati	5	278.58	31.61	562	373	468	37.26
24	Machhali	6	424.92	42.62	641	376	509	57.25
25	Borna	5	290.03	31.67	644	381	513	40.24
26	Dhamunwadi	5	138.57	21.70	435	383	409	26.70
27	Lingi	5	620.78	39.97	749	388	569	70.68
28	Gunwara	5	162.49	33.47	685	391	538	43.25
29	Saraswati	6	287.76	36.29	715	393	554	46.67
30	Abujwadi	3	21.73	6.25	440	397	419	7.45
31	Padmavati	3	38.52	9.02	437	408	423	10.74
32	Waghora	4	34.12	11.72	463	410	437	14.88
Total			**3258.67**	**362.67**	**8709**	**6094**	**7412**	**480.33**
Mean			**203.67**	**22.67**	**544**	**381**	**463**	**30.20**

where a is the area enclosed between a given contour within the basin and basin boundary, and A is the total area of the basin. The second ratio is h/H, where h is the height of the contour above the base level of the stream mouth and H is the total height of the basin with reference to the same base.

The hypsometric integral (H) was calculated as follows:

$$H = (\text{elevation mean} - \text{elevation minimum})/(\text{elevation maximum} - \text{elevation mean})$$

(Keller & Pinter 1996).

The hypsometric integrals calculated for the 32 sub-basins of Godavari River in the Parbhani and Nanded area are presented in Table 4. The magnitude range is 0.25–0.64. The mean H value for the sub-basins in the northern part of the river is 0.45, which is marginally lower than that of the sub-basins in the southern part (0.44). The H values of the Asna and Sita sub-basins, which are located around the NW–SE-trending lineament (Babar *et al.* 2011), are 0.41 and 0.42, respectively. It was noticed that the moderate–high values in the middle part of the study area coincide with the SL anomalies, whereas those for the eastern part correspond

Table 4. *Morphometric attributes for geomorphic indices of active tectonics of sub-basins of the Godavari River Basin in the Parbhani and Nanded districts of Maharashtra*

Sub-basin No.	Name of sub-basin/watershed	Elongation ratio	Asymmetry factors	Stream gradient to length ratio	Hypsometric integral
Sub-basins in the northern part of the Godavari River					
1	Jamb	0.79	48.93	4.85	0.33
2	Ashti	0.66	46.71	3.95	0.64
3	Zari	0.98	71.29	3.59	0.27
4	Masala	0.64	34.59	3.42	0.63
5	Loni	0.62	53.02	3.12	0.58
6	Vazur	0.68	67.52	2.24	0.46
7	Indrayani	0.62	57.73	5.65	0.26
8	Khadki (Vajhur)	0.67	46.04	2.85	0.47
9	Pingalgad	0.46	66.06	2.92	0.38
10	Khadki	0.69	63.29	3.50	0.46
11	Alegaon	0.66	46.22	3.68	0.44
12	Sugaon	0.68	57.38	3.58	0.39
13	Urwashi Ghat	0.61	48.65	3.48	0.60
14	Asna	0.78	27.91	5.81	0.41
15	Barod	0.60	68.14	9.05	0.45
16	Sita	0.63	27.52	5.02	0.42
Total		**10.77**	**831**	**66.71**	**7.19**
Mean		**0.67**	**51.94**	**4.17**	**0.45**
Sub-basins in the southern part of the Godavari River					
17	Kankadi	0.71	68.14	7.86	0.39
18	Dhangarwadi	0.84	57.28	4.80	0.58
19	Bhanagi	0.61	56.10	4.50	0.52
20	Sangvi	0.64	48.84	5.60	0.32
21	Jhod	0.75	25.53	7.05	0.28
22	Dhond	0.67	24.90	5.85	0.25
23	Galati	0.60	29.51	6.33	0.48
24	Machhali	0.55	47.99	7.11	0.40
25	Borna	0.61	47.36	8.11	0.60
26	Dhamunwadi	0.61	31.45	2.92	0.35
27	Lingi	0.70	56.04	3.33	0.44
28	Gunwara	0.43	40.08	8.53	0.39
29	Saraswati	0.53	48.59	7.12	0.42
30	Abujwadi	0.84	21.67	4.10	0.60
31	Padmavati	0.78	74.46	3.87	0.59
32	Waghora	0.56	58.51	6.50	0.46
Total		**10.43**	**736.45**	**93.58**	**7.07**
Mean		**0.65**	**46.03**	**5.85**	**0.44**

to the NW–SE-trending lineament. However, there are sub-basins with moderate and high values other than those of the above-mentioned area. Singh (2008*b*) argued that H is a useful parameter for assessing the nature of active tectonic deformation. Whether tectonics or erosion shapes the watersheds is also revealed.

Stream gradient to length ratio (SL)

This is the ratio of $(H_1 - H_2)$ to $(\ln L_2 - \ln L_1)$, where H_1 and H_2 are the elevations of each end of a given reach, and L_1 and L_2 are the distances from each end of the reach to the source (Hack 1973). The SL index can point out areas of anomalous uplift. The SL values for the 32 sub-basins ranges from 2.24 to 9.05. The mean for the rivers north of the Godavari River is 4.17, which is lower than that of the rivers in the south (5.85) (Table 4).

Valley floor width to valley height ratio

The ratio of valley floor width to valley height (Vf) is expressed as:

$$\mathrm{Vf} = 2\mathrm{Vfw}/(\mathrm{Eld} - \mathrm{Esc}) + (\mathrm{Erd} - \mathrm{Esc})$$

where Vfw is the width of valley floor, and Eld and Erd are the ‘elevations of the left and right valley

Table 5. *Valley floor width to valley height ratios of the Godavari River with their locations (Fig. 2)*

Segment No.	Location	Latitude	Longitude	Erd	Eld	Esc	Vfw	Vf
i	Changatpuri	19° 18′ 05″ N	76° 08′ 00″ E	411.8	412.3	402.5	287.3	30.1
ii	Nathra	19° 16′ 35″ N	76° 13′ 15″ E	410.3	402.2	399.2	295.5	41.9
iii	Dhalegaon	19° 13′ 18″ N	76° 21′ 55″ E	399.2	397.6	386.6	284.0	24.1
iv	Gangamasla	19° 12′ 07″ N	76° 21′ 17″ E	398.5	396.9	385.8	287.3	24.1
v	Gunjthadi	19° 06′ 21″ N	76° 19′ 30″ E	397.8	391.3	385.3	293.2	31.7
vi	Mogra	19° 06′ 21″ N	76° 19′ 30″ E	398.9	390.5	384.8	285.2	28.8
vii	Vita	19° 04′ 28″ N	76° 28′ 38″ E	393.7	390.1	384.2	283.6	36.8
viii	Mudgal	19° 05′ 22″ N	76° 29′ 39″ E	392.7	390.6	384.0	284.3	37.2
ix	Rampuri	19° 06′ 45″ N	76° 34′ 45″ E	398.6	388.0	382.3	290.2	26.4
x	Dharasur	19° 03′ 18″ N	76° 38′ 40″ E	386.2	391.3	380.0	292.3	33.4
xi	Dasalgaon (Gangakher)	19° 01′ 12″ N	76° 43′ 35″ E	392.2	382.3	379.2	290.5	36.1
xii	Vajhur	19° 03′ 54″ N	76° 50′ 35″ E	373.0	376.2	371.6	281.6	46.9
xiii	Jamulbet	19° 03′ 09″ N	76° 55′ 31″ E	379.2	378.7	372.6	302.8	47.7
xiv	Kalegaon	19° 06′ 30″ N	76° 59′ 12″ E	373.6	379.3	371.3	282.5	54.9
xv	Koteshwar	19° 06′ 48″ N	77° 01′ 35″ E	378.1	376.2	368.7	292.3	34.6
xvi	Satephal	19° 06′ 30″ N	77° 06′ 06″ E	384.8	376.3	367.4	293.2	22.3
xvii	Someshwar (Rahti)	19° 06′ 25″ N	77° 12′ 18″ E	372.3	371.6	361.0	314.5	28.7
xviii	Thugaon	19° 07′ 23″ N	77° 16′ 00″ E	361.7	362.3	356.2	290.3	50.1
xix	Wajegaon	19° 09′ 01″ N	77° 20′ 05″ E	358.6	362.8	354.7	296.7	49.4
xx	Devapur	19° 04′ 39″ N	77° 24′ 55″ E	361.2	357.2	351.3	289.3	36.6
Mean Vf								**38.44**

Erd, elevation of the right valley divide; Eld, elevation of the left valley divide; Esc, elevation of the valley floor; Vfw, valley floor width; $Vf = 2Vfw/(Eld-Esc) + (Erd-Esc)$ (after Bull & McFadden 1977).

divides, respectively, and Esc is the elevation of the valley floor' (Bull & McFadden 1977). The ratio is generally used to determine the role of tectonic uplift in the different geomorphic surfaces. Vf is calculated for 20 reaches of the main trunk of the Godavari River. The locations for the same are shown in Figure 2 (segments i–xx) and the values are given in Table 5. The Vf values obtained for the Godavari River show relatively high values along the east–west-flowing part of the Godavari River (i.e. segments at Vazur, Jamulbet, Kalegaon, Thugaon and Wajegaon: Table 5) compared to that for the WNW–ESE part of the Godavari at locations from segments i to xi, except for Nathra (i.e. Vf = 41.9 for segment ii) (see Table 5 and Fig. 2 for the locations), where the values of Vf were found to be low (i.e. <40). The NW–SE trend of the river (i.e. at Thugaon, Wajegaon and Devapur) (Table 5) also has low Vf values. Compared to the east–west segment, the WNW–ESE and NW–SE trends of the river show lower Vf values. This probably suggests the effect of neotectonic activity on the WNW–ESE and NW–SE trend of the river. The Vf values in Table 5 are high (i.e. >22.3, with a maximum of up to 54.9), and high Vf values indicate that the valleys are broader and occur in downstream areas of the river. This index differentiates between (i) broad-floored valleys that are associated with low uplift rates and show relatively high values of Vf and (ii) 'V'-shaped valleys where stream incision is dominant; 'U- shaped valleys have Vf > 10, as these areas witness major lateral erosion due to right lateral motion (Nagare 2014).

The Vf ratio is a good measure for checking whether the river is incising (Bull & McFadden 1977; Verrios *et al.* 2004; Farooq *et al.* 2015). The higher the rate of uplift, the more incised the valley cross-section profile.

Late Quaternary changes in the fluvial regime of western Maharashtra possibly indicate neotectonics (Rajaguru & Kale 1985). However, no evidence in support of this has been reported from the Nanded region so far. The landscapes undergoing uplift should display (e.g. Bull & McFadden 1977):

- a very low elongation ratio for tectonically disturbed rivers;
- an asymmetry factor significantly greater or less than 50, suggesting slight tectonic tilt along the NW–SE direction;
- a high hypsometric integral, indicating deep incision and rugged relief;
- low values of Vf, reflecting valleys occupied by incising streams.

Lineaments identified based on straight courses of streams

Lineaments in the study area appear as, or in terms of, linear stream channels, the alignment of dark tone and the alignment of vegetation observed in images. These are, linear to slightly curvilinear, geological features of local or regional extent, and are considered to be zones of structural weakness that are of geological, geomorphological and hydrological relevance. Usually, streams are sinuous: hence, the lineaments are identified when the streams, tributaries or rivers in the area exhibit straighter courses (Fig. 6). The straight courses are confirmed in the field. A brief description of these lineaments is provided in Table 6. The lineaments could either be faults or dykes (see Misra & Mukherjee 2015*a*, *b* for a different context). The dyke lineaments could not be traced on images as these, unlike those from other parts of the Deccan Trap, are of smaller length and are not exposed as elevated ridges. Most of the dykes fed the overlying basaltic flow. The length of the lineaments varies from 0.2 (L_{15}) to 9.4 km (L_7).

Preferred stream orientations are used to reconstruct neotectonics (Cantamore *et al.* 1996). Structural features (joints, faults and lineaments) may produce essentially straight rivers with minimum meandering (Twidale 2004). Joints and faults may produce short linear sections of rivers, typically a few tens of metres long. Thus, it is interpreted that the major orientation of the straight course of the UG stream, with limited meander, is (thrust) fault-controlled (L_6).

Minor deformation is observed in the Quaternary deposits along the junction of L_4 and L_5 (Fig. 5a, b). The deformation is not observed along other lineaments, as the other lineaments are covered by black cotton soil. Hence, detailed geophysical surveys along these lineaments would be required

Geomorphometric characterization: stream characters

The response of streams to tectonic deformation is demonstrated by channel deflections (Whitney & Hengesh 2015). We have observed deflection of streams, such as sharp knee-bend turns, off-sequent streams and a few anomalous features of streams, in the study region.

Off-sequent streams

These streams drain to the SE following the general slope. Figure 6a–d shows evidence of off-sequent streams. In particular, the stream at Degaon (Fig. 6a) flows approximately 1 km in the opposite direction to the flow of the major tributary and twice has right angled bends: one between Khadkut

Table 6. *Description of the lineaments in brief*

Sr. No	Lineament	Length (km)	Direction	Name of the stream (if any)
1	L_1	6.9	N01° E–S01° W	Son Nadi (local name)
2	L_2	4.1	N25° W–S 25° E	Son Nadi (local name)
3	L_3	8.5	N78° E–S 78° W	Godavari River
4	L_4	0.8	N30° W–S30° E	Kottirth Nala
5	L_5	2.5	N05° W–S05° E	Godavari River
6	L_6	6.0	N38° W–S38° E	Urvashi Ghat Nala
7	L_7	9.4	N38° W–S38° E	Asna Asegaon (Extension of Urvashi Ghat Lineament)
8	L_8	2.2	N70° E–S70° W	Asna Hadidapur
9	L_9	1.3	N78° W–S78° E	Puyni Nala
10	L_{10}	1.4	N29° E–S29° W	Taroda Khurd Nala
11	L_{11}	0.9	N25° E–S25° W	Sangvi Buzurg Nala
12	L_{12}	0.3	N38° E–S38° W	Degaon Nala
13	L_{13}	0.8	N35° W–S35° E	Bramhanwada Nala
14	L_{14}	0.4	N10° W–S10° E	Bramhanwada Nala
15	L_{15}	0.2	N40° E–S40° W	Amdura Nala
16	L_{16}	1.0	N75° W–S75° E	Wasri Nala
17	L_{17}	0.8	N40° E–S40° W	Kikki Nala
18	L_{18}	4.6	N45° E–S45° W	Sita Nala
19	L_{19}	1.6	N68° W–S68° E	–
20	L_{20}	5.5	N34° E–S34 °W	–
21	L_{21}	7.5	N12° E–S12° W	Sita Nala
22	L_{22}	1.9	N32° W–S32° E	Sita Nala
23	L_{23}	0.7	N48° E–S48° W	Sita Nala

and Degaon, and other just before joining the major river. The lower right-angled bend of the stream is controlled by lineament L_{12}. Similarly, the right-angled turn (knee bend) of the stream in Figure 6b is controlled by lineament L_4, and in Figure 6c it is controlled by lineament L_{18}. The off-sequent stream in Figure 6d is not associated with lineaments, but all the streams show right-angle turns and localized meanders before joining the main river. Twidale (2004) concluded that straight channels imply control by fractures, either exposed or induced by underprinting.

Sharp knee-bend turns of streams: distorted streams

Some of the streams, which are not off-sequent streams, show sharp knee-bend turns. Usually, streams flow sinuously. Streams flowing in an almost straight direction indicate that they are controlled by a discontinuity or hidden linear structure. Streams in Figure 7a–c show a straight course with sharp knee-bend turns. In Figure 7d, two streams flow in opposite directions to one another in a straight line before they meet.

In Figure 7, two streams converge and diverge. Streams in the NW corner flow towards the SE, and the streams in the SE corner flow towards the west. However, the former stream suddenly changes direction and flows towards the SW, while the latter, instead of flowing towards the west, goes towards the south.

Discussion

Field evidence

Tectonic features in the form of thrusts associated with antiform and fault-related folds, reported from the northern part of the Godavari River, are reported from Zone 3 (Kaplay *et al.* 2013). Note that the dip direction of these thrusts (such as the Kamtha thrusts) is also towards the west, which corroborates with that of the causative fault reported by Srinagesh *et al.* (2012). Most of Nanded City is located on the estern side of this causative fault.

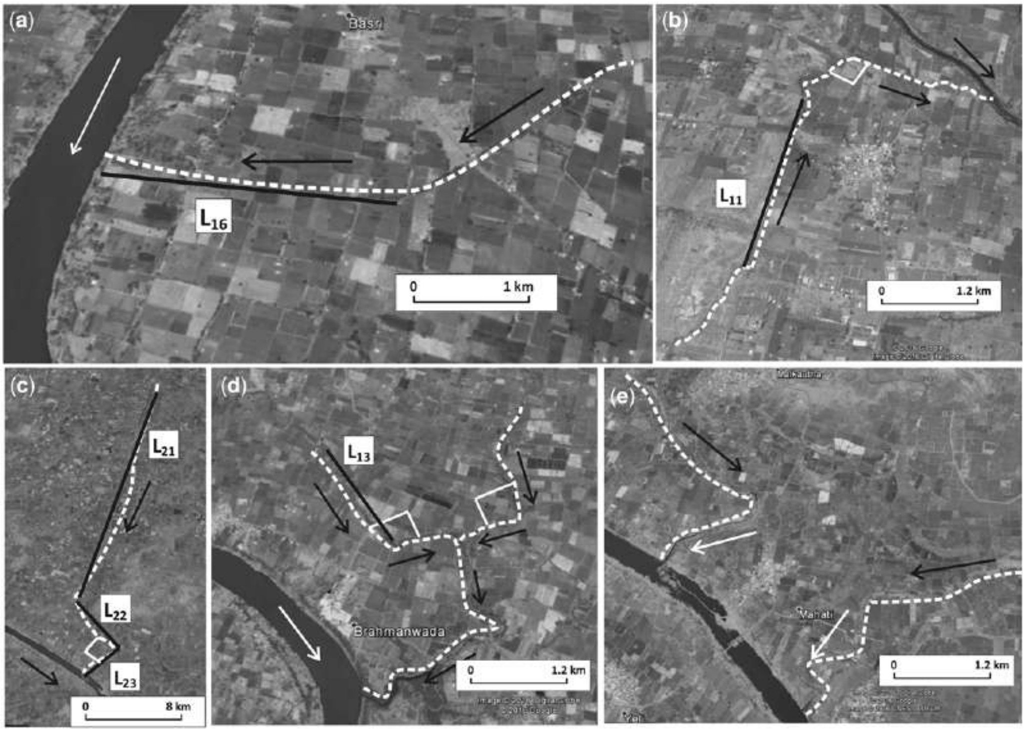

Fig. 7. Sharp knee-bend turn and anomalous behaviour of streams: (**a**) lineament L_{16}; (**b**) lineament L_{11}; (**c**) lineaments L_{21}–L_{23} control the straight course of the streams; (**d**) lineament L_{13} and L_{14} control the knee-bend turn of streams; and (**e**) anomalous behaviour of streams (convergence and divergence of streams before joining the main stream). The arrows indicate the direction of the flow of streams.

Deformation in Quaternary deposits. The deformation observed at the junction of L_4 and L_5 (Fig. 4a, b) is neotectonic, as it is reported in Quaternary deposits. These areas of deformation are reported from Zone 3 and are located on the northern side of the Godavari River. The straight course of the Urvashi Ghat stream that flows through the UG Lineament (which itself is a manifestation of a thrust) and the occurrence of deformation at the junction of lineaments L_4 and L_5 suggest neotectonics of the drainage system in Zone 3. Normal faults, with off-set cutting through the black cotton soil (Fig. 5c), are also reported in Zone 3.

Anomalous drainage, lineaments and microseismicity. Anomalous drainage patterns can indicate obscure geological structures and neotectonics (Jackson *et al.* 1998; Goldsworthy & Jackson 2000; Burrato *et al.* 2003; Vannoli *et al.* 2004; Delcaillau *et al.* 2006; Hodgkinson *et al.* 2006). Turns of 90° and anomalous behaviour of streams in general indicate that the drainage pattern of the region is controlled by subsurface discontinuities or structures (Babar *et al.* 2000). In the study region, channel anomalies are observed that could mean hidden rift or subsurface fault(s) (Fig. 7). Anomalous drainage, which includes off-sequent streams, sharp knee-bend turns and straight courses (Fig. 7), is confined on the northern side of the Godavari River in Zone 3. No anomalous drainage features are observed on the southern side of the Godavari River.

The microseismicity observed in the Nanded region is also confined to the northern side of the Godavari River, with no event reported from the southern. The microseismicity is restricted to within 10 km^2 and focal depths of these earthquakes range from 0 to 2 km, indicating that the hypocentres of quakes extend into the granitic basement. The recent digging of deep bore wells for groundwater, nearer to the UG Lineament, revealed that granite occurs approximately 200 m below the basalt (Fig. 1b). The spatial distribution of the microseismicity is shown in Figure 1b. The earlier events in 2006–2007 took place on the eastern side and the later events happened towards the south. Thus, the microseismicity shifted from the east towards the west: that is, towards the straight course of the stream, here named here as the Uravashi Ghat stream. This straight course of the stream is inferred from satellite images as NW-trending lineaments (Srivastava 2007), and we refer this lineament as the UG Lineament.

The UG lineament (L_6) in the study area is approximately 6 km long. It passes through the Wadi and Jangamwadi areas, and joins the Godavari River near the Urvashi Ghat. Google Earth Image enabled us to trace L_6 further NW for up to 9.4 km, and it is marked as L_7 in Figure 4. The lineament thus continues up to Wasamat, approximately 25 km from Nanded. Interestingly, an earthquake in 1942 with a magnitude of 3.7 (intensity IV), with an epicentre location of 19° 30′ N latitude and 77° 0′ E longitude, was reported by Rastogi (2001). Thus, it is interesting to note that microseismicity is reported at the SE end of the UG Lineament (near Nanded) and past seismicity is reported nearer to the NW end of this lineament (near Wasmat: the dashed circle in the top left-hand corner of Fig. 4a). However, no field evidence of deformation has been observed in the alluvium deposits.

Srinagesh *et al.* (2012) interpreted that thrusting along a NW-trending fault coincides with a local stream that joins the Godavari River, south of Nanded City. This fault can be correlated with the Urvashi Ghat Lineament. The depth of the UG Lineament is interpreted to be 4 km along its SE end (Srinagesh *et al.* 2012). The straight course of the Urvashi Ghat stream (Fig. 3) suggests the presence of a subsurface discontinuity. The UG Lineament continues in the underlying granite basement: hence, it can be interpreted as a basement lineament, the manifestation of which is expressed in the overlying Deccan basalt.

Prior to this activity in Nanded, in the proximity of Nanded City, at a distance of about 146 km SE of Nanded, a devastating earthquake of magnitude 6.3 struck the Killari region on 30 September 1993 along a hidden fault that coincides with the Tirna Lineament (Babar *et al.* 2000; Chetty 2006; Mukhopadhyay *et al.* 2006).

The trend of most of the lineaments (52%) observed in the study area is NE, whereas 48% trend to the NW (Fig. 4a). The regional lineament trends worked out by earlier workers are as follows. Two NE–SW lineaments, one between Khandwa and Edlabad, and the other one between Partur and Kurudwadi (Harinarayana *et al.* 2007). The Tapti Lineament, traceable from Ambikapur in Madhya Pradesh to Daman on the Indian western coast, trends NE (Powar & Patil 1980). The Koyna Lineament, a surface manifestation of the Koyna Rift, trends NE. The Panvel Lineament, from Silvassa to Panvel, that corresponds to the Panvel flexure also shows a similar trend (Powar & Patil 1980). NE–SW lineaments have also been reported near Mumbai at Salher and Ratanagarh by Misra *et al.* (2014).

NE–SW lineaments from the study area match those reported between Khandwa and Edlabad, Partur and Kurudwadi (Harinarayana *et al.* 2007), at Salher and Ratanagarh near Mumbai (Misra *et al.* 2014), and the Panvel and the Tapti lineaments (Powar & Patil 1980).

The Godavari lineaments (lineaments in the Godavari Basin) trend NW and correspond to the margins of the Godavari Rift (Powar & Patil 1980). The Mahanadi Lineament, with a NW trend, cuts across the Deccan Volcanic Province at its eastern extremity (Powar & Patil 1980). A NW-trending lineament, the Kurudwadi Lineament (about 240 km SW of the study area), can be traced near Gulbarga, Kurudwadi and extends north to Mumbai (Harinarayana *et al.* 2007). Structural disturbances at deep crustal depth are speculated along this lineament (Peshwa & Kale 1997) from observations of satellite imagery and field verification. Six NW–SE fault/lineament zones, with known tectonic features in-between Kurudwadi and Partur, have been reported (Patro 2002; Harinarayana *et al.* 2007). NW–SE-trending Kaddam fault lineaments (about 100 km NE of the study area: Sangode *et al.* 2013) can be traced near Kinwat, Maharashtra.

The NW-trending lineaments from the study area match with the Godavari Lineament (Powar & Patil 1980), the Kurudwadi Lineament (Peshwa & Kale 1997), fault lineaments (Patro 2002; Harinarayana *et al.* 2007), lineaments from Karla reported by Misra *et al.* (2014) and the Kaddam fault lineaments (Sangode *et al.* 2013). Also noted was that the NW trend of the UG Lineament matches with the direction of the seismically active Tirna tributary (Killari), 140 km SW of the UG Lineament.

The north trend of the L_5 lineament (Figs 4a & 6b) from the study area matches with the Trans-Deccan Lineament, which is a conspicuous lineament that follows an arcuate north–south trend from Kota in the north to Kurudwadi in the south (Powar & Patil 1980), and the dominant north–south-orientated lineaments from strike-slip fault zones near the west coast reported by Misra *et al.* (2014) (see also Misra & Mukherjee 2015*a*, *b*; Misra *et al.* 2015 for the regional geology). The Godavari River here flows along an almost straight course for approximately 2.5 km. The width of the Godavari River along this section is approximately 220 m. Interestingly, the off-sequent stream (Fig. 6b) is sub-parallel to the north–south-trending Godavari River. The north–south-trending Godavari River in this section matches with the trend of the lineaments of the West Deccan Strike-slip Zone (Misra *et al.* 2014). Thus, the trends of the lineaments from the study area show a similar trend to that shown by the lineaments of the Deccan Volcanic Province.

Morphometric analysis

Morphometric data, combined with seismic and geomorphic data, is a valuable tool in determining relative levels of neotectonic activity and in providing data for seismic hazard assessment. The elongation ratio constrains the elongate nature of the basin. The hypsometric integral quantifies active tectonics (Singh 2008*b*).

Spatial analysis of basins. A basin elongation ratio <0.5 indicates the basin is tectonically active, values ranging between 0.5 and 0.75 reflect slightly/moderately active basins, and those >0.75 reflect inactive basins (Cuong & Zuchiewicz 2001). The elongation ratio, for most of the sub-basins (24 out of 32), is in the range 0.5–0.75, indicating that most of the sub-basins are slightly/moderately tectonically active. As the entire study area shows that the elongation ratio is poorly related to tectonics, the area was divided into the northern and southern sides.

The value of mean elongation ratio for sub-basins in the northern part of the Godavari River is slightly more (0.67) than that in the southern part (0.65). Basins in southern part of the Godavari River are more elongate (low values of the elongation ratio) than in the northern part (Fig. 8a).

Hypsometric data acquired from the Shuttle Radar Topography Mission digital elevation model (SRTM DEM) and other sources can be utilized for analysis of the watershed or basins of any dimensions (Rosenblatt & Pinet 1994; Hurtez *et al.* 1999). It is one of the significant tools in assessing and comparing the geomorphic evolution of various landforms. The present analysis covers basins where thrusts have been ascertained from geophysical studies (e.g. the UG Lineament) and fieldwork (Kamtha thrusts).

The southern part has slightly lower average hypsometric integral values (0.45) than the northern part (0.44). The entire area can further be subclassified into six zones (Figs 2, 8 & 9): three on the northern side of the Godavari River, and the other three on the southern side. Spatial analysis was carried out on these zones in the line of Singh (2008*b*). This was undertaken to find out the specific influence of the structures in particular areas:

- Zone 1: the elongation ratio on the northern side in this zone is higher (average: 0.72) than on the southern side (average: 0.529), and the hypsometric integral on the northern side is the same (average: 0.49) as that on the southern side (average: 0.49).
- Zone 2: the elongation ratio on the northern side in this zone is higher (average: 0.61) than on the southern side (average: 0.58), and the hypsometric integral on the northern side is slightly higher (average: 0.41) than on the the southern side (average: 0.39)
- Zone 3: the class named here as the Nanded Structural Class shows the exact opposite trend of elongation ratio and hypsometric integral to that of the entire basins in the study area. The

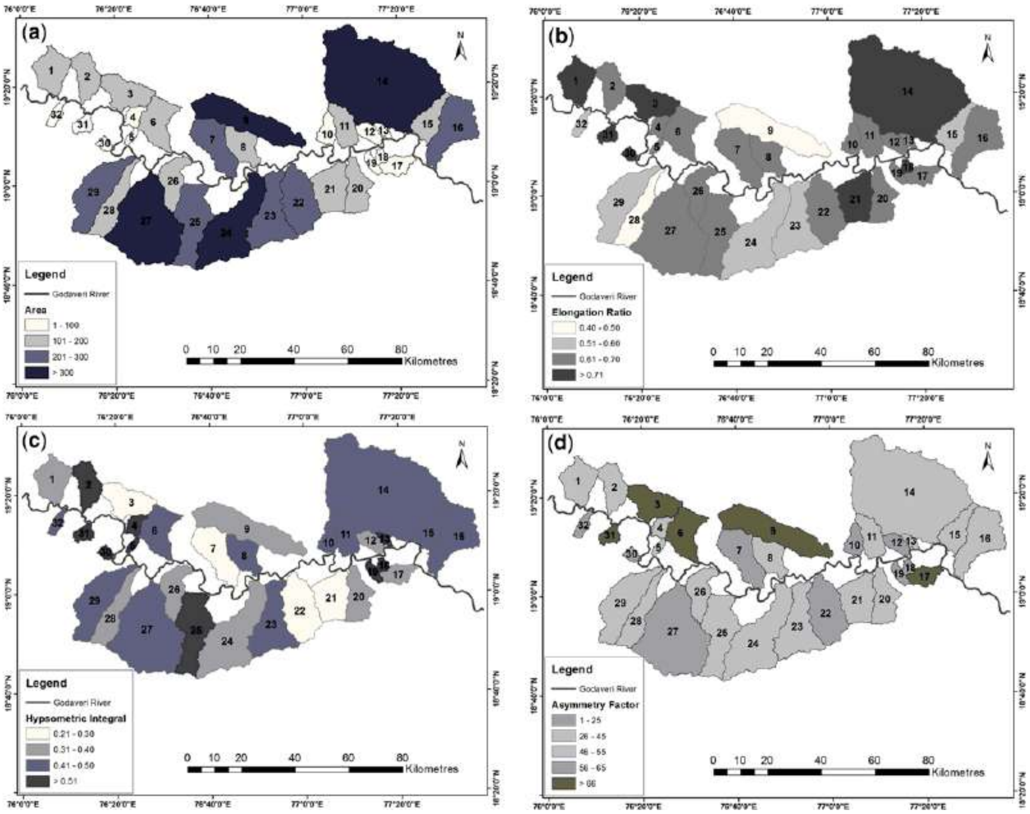

Fig. 8. (**a**) Basin area, (**b**) elongation ratios, (**c**) the hypsometric integral and (**d**) the basin asymmetry factor.

elongation ratio of the northern side is slightly less (average: 0.63) than on the southern side (average: 0.64). The low values of elongation ratio on the northern side suggest that this side (i.e. the northern side) is more elongate than the southern part. This is attributed to structural deformation observed in the northern region. Further, the northern part has a lower range of hypsometric integral values (average: 0.45) than the southern part (0.50) (Fig. 8b), indicating that a comparatively lesser proportion of the area is elevated in the southern part of the study area. North of this zone, the UG Lineament basin shows the highest hypsometric integral value (0.60).

We filtered out sub-basins 12, 13 and 14 on northern side, and 17, 18 and 19 on the southern side to find out whether there were any strong correlations, as sub-basins 12, 13 and 14 show deformation (Kaplay *et al.* 2013) but 17, 18 and 19 do not. We found that the elongation ratio for sub-basins 12, 13 and 14 (on the northern side) shows an average magnitude of 45.75, while for sub-basins 17, 18 and 19 (on the southern side) it is 63.39. The strong difference between the values across the river may be attributed to the UG Lineament, and the associated seismicity and deformation. This type of filtering was also performed for the hypsometric integral and asymmetry factor but did not bring to light any major differences.

Sub-basin 14, on the northern side in Zone 3, has the largest area. This is the sub-basin where the Kamtha thrusts are reported. This is also the zone where deformation in the Black Cotton Soil (BCS) has been observed. The UG fault lineament falls in sub-basin 13. Sub-basin 12 contains deformed Quaternary deposits. The microseismicity mostly covers sub-basins 13 and 14.

The influence of tectonics is variable on both flanks around Nanded. It is more pronounced on the northern side than on the southern side, as shown by the higher values of the hypsometric integral. This is supported by the presence of the UG Thrust Lineament (L_6) and the Kamtha thrusts in the basalts on the northern side. Minor deformation, observed in Quaternary deposits near the junction of two lineaments (L_4 & L_5), also falls on the northern

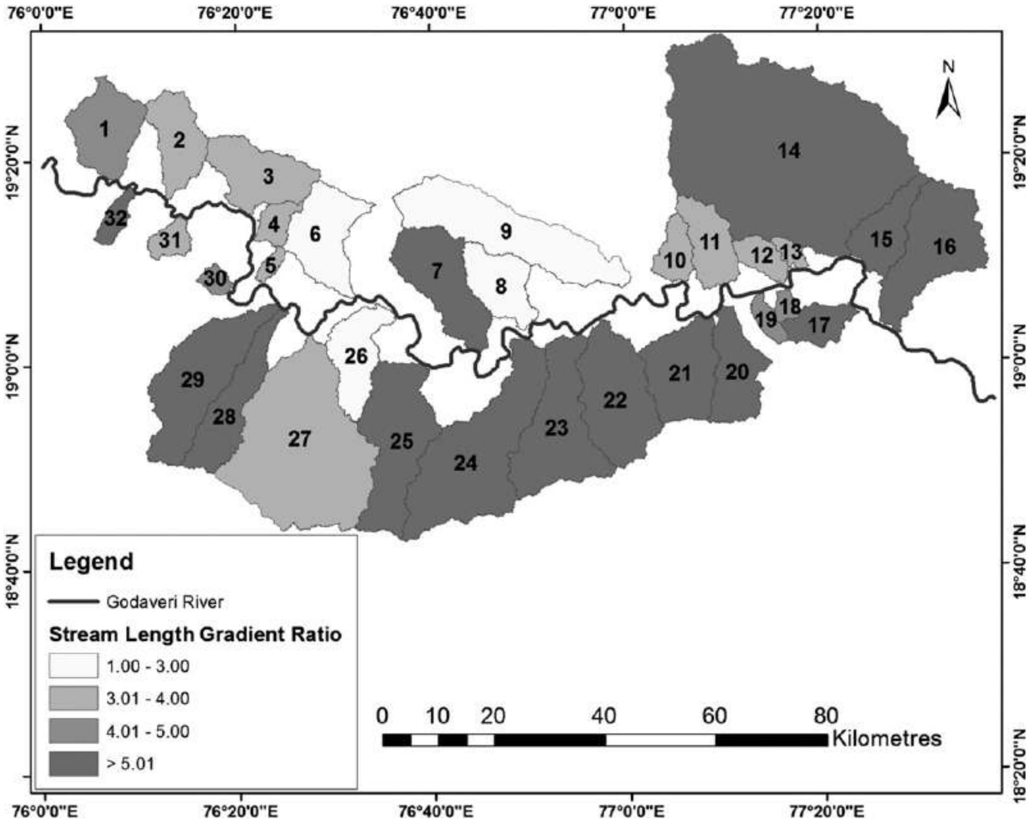

Fig. 9. Stream gradient to length ratio.

side. The northern side of this zone is characterized by lineaments and the anomalous stream courses.

The influence of tectonics is less on the southern side, as indicated by a comparatively high elongation ratio. This is also well supported by the absence of lineaments and anomalous stream courses on this side. Furthermore, no deformation is observed here.

In addition to the elongation ratio and hypsometric integral, the asymmetry factor was also first analysed for the entire study area then for the three zones. The average asymmetry factor for the northern side is lower (48.34) than on the southern side (55.35).

The asymmetry factor was then studied for different zones (Fig. 8d). In Zone 1, the average value for the asymmetry factor on the northern side (53.15) is less than on the southern side (63.50). In Zone 2, its average value on the northern side is higher (48.89) than on the southern side (47.23). In Zone 3, the average value on the northern side is less (42.87) than on the southern side (63.40). However, the average value for the asymmetry factor on the northern side in Zone 3 is the lowest value obtained (42.87). The asymmetry of the drainage basins on the northern side thus reflects the influence of tectonics on the drainage pattern. Anomalous drainage patterns are confined to this zone.

A comparison of the morphometric parameters for the entire study area shows that when the dataset is subdivided into classes (as per Singh 2008*b* in a different study area), a better relationship arises between the parameters. This is clearly evident from the above observations. Thus, it may be inferred that, although the study area is similar in terms of lithology, the geological structure is significantly different in the eastern part (Zone 3), which is reflected in the different geomorphic parameters. In the northern part of the area, SL values are less (Table 4), even though the rock is basalt. The reason for this is the intense weathering of the rocks. In the southern part of the area with less tectonic activity, the SL values are higher. This means that within the area of same/similar lithology and slope, the SL index fluctuates. The SL index is roughly related to the stream power, while is particularly sensitive to changes in slope and lithology. This sensitivity allows an evaluation to be made of the relationship between possible tectonic activity and rock resistance (Keller & Pinter 1996). Therefore, the index is high in places with resistant rocks/active tectonics. Thus, anomalously high SL values or its fluctuation in rock of uniform resistance is a possible indicator of active tectonics (Keller 1986). Higher values of SL are concentrated in the southern and western zones of the area around Nanded district (Fig. 9).

The area north of Godavari is more deformed than the southern area. Pronounced microseismicity is also found on the northern side of the Godavari River.

Conclusions

The elongation ratio and hypsometric integral have been found to be useful parameters for assessing the nature of active tectonic deformation (Singh 2008*b*); we found the same to be true in this study. The major conclusions derived are as follows:

- In and around the Nanded region (Maharashtra, India), which has been microseismically active since 2006, tectonics are more pronounced on the northern side than on the southern side.
- The influence of tectonics is more prominent in Zone 3 (Figs 2, 8 & 9) on the northern side of the Godavari River, where microseismic activity, the UG Thrust Lineament, the Kamtha thrusts, deformation in Quaternary deposits, and other lineaments and anomalous drainage are confined.
- The influence of tectonics in Zone 3 has also been ascertained by reference to anomalous asymmetry factor values.

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References

Babar, M.D., Kaplay, R.D. & Panaskar, D.B. 2000. Structural control on drainage pattern in the Tirna River Catchment, Central west India. *Indian Journal of Geomorphology*, **5**, 126–133.

Babar, M.D., Ghute, B.B. & Chunchekar, R.V. 2011. Geomorphic indicators of Neotectonics from the Deccan Basaltic Province: a study from the Upper Godavari River Basin, Maharashtra, India. *International Journal of Earth Science and Engineering*, **4**, 297–308.

Bondre, N.R., Duraiswami, R.A., Dole, G., Phadnis, V.M. & Kale, V.S. 2000. Inflated pahoehoe lavas from the Sangamner area of the western Deccan Volcanic Province. *Current Science*, **78**, 1004–1007.

Bondre, N.R., Duraiswami, R.A. & Dole, G. 2004. Morphology and emplacement of flows from the Deccan Volcanic Province, India. *Bulletin of Volcanology*, **66**, 29–45.

Bull, W.B. & McFadden, L.D. 1977. Tectonic Geomorphology north and south of Garlock Fault, California. *In*: Doehring, D.O. (ed.) *Geomorphology in Arid Regions Eighth Annual Geomorphology Symposium*. State University New York, Binghamton, NY, 115–138.

Burbank, D.W. & Anderson, R.S. 2001. *Tectonic Geomorphology*. Blackwell Science, Oxford.

Burrato, P., Ciucci, F. & Valensise, G. 2003. An inventory of river anomalies in the Po Plain, Northern Italy: evidence for active blind thrust faulting. *Annals of Geophysics*, **46**, 865–882.

Cantamore, E., Ciccacci, S., Montedel, M., Fredt, P. & Lupia Palmieri, E. 1996. Morphological and morphometric approach to the study of the structural arrangements of northeastern Abruzzo (Central Italy). *Geomorphology*, **16**, 127–137.

Central Ground Water Board (CGWB). 2012. *Guidelines for Aquifer Mapping*. Government of India, Faridabad.

Chetty, T.R.K. 2006. Contrasting deformational systems and associated seismic patterns in Precambrian peninsular India. *Current Science*, **90**, 942–951.

Cuong, N.Q. & Zuchiewicz, W. 2001. Morphotectonic properties of the Red River Fault Zone in Vietnam: a geomorphic perspective. *Natural Hazards and Earth System Sciences*, **1**, 15–22.

Delcaillau, B., Carozza, J.M. & Laville, E. 2006. Recent fold growth and drainage development: the Janauri and Chandigarh anticlines in the Siwalik foothills, northwest India. *Geomorphology*, **76**, 241–256.

Duraiswami, R.A., Bondre, N.R., Dole, G., Phadnis, V.M. & Kale, V.S. 2001. Tumuli and associated features from the western Deccan Volcanic Province, India. *Bulletin of Volcanology*, **63**, 435–442.

Duraiswami, R.A., Bondre, N.R., Dole, G. & Phadnis, V.M. 2002. Morphology and structure of flow-lobe tumuli from the western Deccan Volcanic Province, India. *Journal of Geological Society of India*, **60**, 57–65.

Duraiswami, R.A., Dole, G. & Bondre, N.R. 2003. Slabby pahoehoe from the western Deccan Volcanic Province: evidence for incipient pahoehoe-aa transitions. *Journal of Volcanology and Geothermal Research*, **121**, 195–217.

Duraiswami, R.A., Bondre, N.R. & Managave, S. 2008. Morphology of rubbly pahoehoe (simple) flows from the Deccan volcanic province: implications for style of emplacement. *Journal of Volcanology and Geothermal Research*, **177**, 822–836.

Farooq, S., Nazish Khan, M. & Sharma, I. 2015. Assessment of active tectonics in Eastern Kumaon Himalaya on the basis of morphometric parameters of Goriganga River Basin. *International Journal of Advancement in Earth and Environmental Sciences*, **3**, 14–21.

Godbole, S.M., Rana, R.S. & Natu, S.R. 1996. Lava stratigraphy of Deccan basalts of Western Maharashtra. *Gondwana Geological Magazine, Special Publications*, **2**, 125–134.

Goldsworthy, M. & Jackson, J. 2000. Active normal fault evolution in Greece revealed by geomorphology and drainage patterns. *Journal of the Geological Society, London*, **157**, 967–981, https://doi.org/10.1144/jgs.157.5.967

Hack, J. 1973. Drainage adjustment in the Appalachians. *In*: Morisawa, M. (ed.) *Fluvial Geomorphology*. George Allen & Unwin, London, 51–69.

Hare, P.W. & Garner, T.W. 1985. Geomorphic indicators of vertical Neotectonics along converging plate margins, Nicoya Peninsula, Costa Rica. *In*: Morisawa, M. & Hack, J.T. (eds) *Tectonic Geomorphology. Proceedings of the 15th Annual Binghamton Geomorphology Symposium, September 1985*. Allen & Unwin, Boston, MA, 75–104.

Harinarayana, T., Patro, B.P.K., Veeraswamy, K., Manoj, C., Naganjaneyulu, K., Murthy, D.N. & Virupakshi, G. 2007. Regional geoelectric structure beneath Deccan Volcanic Province of the Indian subcontinent using magnetotellurics. *Tectonophysics*, **445**, 66–80.

Hodgkinson, J.H., Mcloughlin, S. & Cox, M. 2006. The correlation between physiography and neotectonism in southeast Queensland. *In*: *Proceedings of the Earthquake Engineering Conference AEES2006, Canberra, ACT, Australia*. Australian Earthquake Engineering Society, Sydney, Australia, 195–202.

Hurtez, J.E., Sol, C. & Lucazeau, F. 1999. Effect of drainage area on hypsometry from an analysis of small-scale drainage basins in the Siwalik Hills (Central Nepal). *Earth Surface Processes and Landforms*, **24**, 799–808.

Jackson, J., Van Dissen, R. & Berryman, K. 1998. Tilting of active folds and faults in the Manawatu region, New Zealand: evidence from surface drainage patterns. *New Zealand Journal of Geology and Geophysics*, **41**, 377–385.

Kale, V.S. & Shejwalkar, N. 2008. Uplift along the western margin of the Deccan Basalt Province: is there any geomorphic evidence? *Journal of Earth System Sciences*, **117**, 959–971.

Kaplay, R.D., Vijay Kumar, T. & Sawant, R.N. 2013. Field evidence for deformation in Deccan traps in microseismically active Nanded area, Maharashtra. *Current Science*, **105**, 1051–1052.

Keller, E.A. 1986. Investigation of active tectonics: use of surficial Earth processes. *In*: Wallace, R.E. (eds) *Active Tectonics Studies in Geophysics*. National Academic Press, Washington, DC, 136–147.

Keller, E.A. & Pinter, N. 1996. *Active Tectonics Earthquakes, Uplift and Landscape*. Prentice-Hall, Englewood Cliffs, New Jersey.

Madhnure, P. 2006. *A Report of Groundwater Survey in Nanded District, Maharashtra. Central Region*. Central Groundwater Board, Nagpur, India.

Madhnure, P. 2014. Groundwater exploration and drilling problems encountered in basaltic and granitic terrain of Nanded district, Maharashtra. *Journal Geological Society of India*, **84**, 341–351.

Misra, A.A. & Mukherjee, S. 2015*a*. *Tectonic Inheritance in Continental Rifts and Passive Margins*. Springer Briefs in Earth Sciences. Springer, Cham, Switzerland.

Misra, A.A. & Mukherjee, S. 2015*b*. Dyke–brittle shear relation in the western Deccan Traps near Mumbai, India. *Paper presented at the Tectonic Studies Group Annual Meeting*, 6–8 January 2015, Grant Institute, University of Edinburgh, UK.

Misra, A.A., Bhattacharya, G., Mukherjee, S. & Bose, N. 2014. Near N–S paleo–extension in the western Deccan region, India: does it link strike–slip tectonics with India–Seychelles rifting? *International Journal of Earth Sciences*, **103**, 1645–1680.

Misra, A.A., Sinha, N. & Mukherjee, S. 2015. Repeat ridge jumps and microcontinent separation: insights from NE Arabian Sea. *Marine and Petroleum Geology*, **59**, 406–428.

Molin, P., Pazzaglia, F.J. & Dramis, F. 2004. Geomorphic expression of active tectonics in a rapidly-deforming forearc, Sila Massif, Calabria, Southern Italy. *American Journal of Science*, **304**, 559–589.

Mukherjee, S. 2013. *Deformation Microstructures in Rocks*. Springer Geochemistry/Mineralogy. Springer, Berlin.

Mukherjee, S. 2014*a*. Review of flanking structures in meso- and micro-scales. *Geological Magazine*, **151**, 951–974.

Mukherjee, S. 2014*b*. *Atlas of Shear Zone Structures in Meso-scale*. Springer Geology. Springer, Cham, Switzerland.

Mukherjee, S. 2015. *Atlas of Structural Geology*. Elsevier, Amsterdam.

Mukhopadhyay, S., Mishra, O.P., Zhao, D. & Kayal, J.R. 2006. 3-D seismic structure of the source area of the 1993 Latur, India, earthquake and its implications for rupture nucleations. *Tectonophysics*, **415**, 1–16.

Nagare, V.B. 2014. Calculating the morphotectonic indices of the Mula River Basin, Western part of Maharashtra, India: a GIS approach. *Galaxy: International Multidisciplinary Research Journal*, **3**, 230–237.

Nanded District Gazetteer. 1971. Section on Geology, contributed by the Geological Survey of India, Calcutta, Maharashtra State Gazetteers, Government of Maharashtra, Nanded District (First Edition). Directorate of Government Printing, Stationary and Publications, Maharashtra State, Bombay, India.

Patro, B.P.K. 2002. *A magnetotelluric study of crustal geoelectric structure in western India in relation to seismotectonics of the Deccan trap region*. PhD thesis, Osmania University, Hyderabad, India.

Peshwa, V.V. & Kale, V.S. 1997. Neotectonics of the Deccan trap province: focus on Kurudwadi lineament. *Journal of Geophysics*, **18**, 77–86.

Powar, K.B. & Patil, D.N. 1980. Structural evolution of the Deccan Volcanic Province: a study based on LANDSAT-1 imageries. *In*: *Proceedings of the 3rd India Geological Congress, Poona*. University of Poona, Poona, India, 235–253.

Rajaguru, S.N. & Kale, V.S. 1985. Changes in the fluvial regime of Western Maharashtra upland rivers during Late Quaternary. *Journal of Geological Society of India*, **26**, 16–27.

Rajaguru, S.N., Kale, V.S. & Badam, G.L. 1993. Quaternary fluvial systems in Upland Maharashtra. *Current Science*, **64**, 817–822.

Rastogi, B.K. 2001. Seismology and seismic events of western India, Special issue on earthquake, Maeers. *Maharashtra Institute of Technology Pune Journal*, **IX**, 70–80.

Rosenblatt, P. & Pinet, P.C. 1994. Comparative hypsometric analysis of Earth and Venus. *Geophysical Research Letters*, **21**, 465–468.

Sangode, S.J., Mesharm, D.C., Kulkarni, Y.R., Gudadhe, S.S., Malpe, D.B. & Herlekar, M.A. 2013. Neotectonic response of the Godavari and Kaddam Rivers in Andhra Pradesh, India: implications to quaternary reactivation of old fracture system. *Journal of Geological Society of India*, **81**, 459–471.

Schumm, S.A. 1956. The evolution of drainage systems and slopes in bad lands at Perth, Amboi, New Jersey. *Geological Society of American Bulletin*, **67**, 597–646.

Singh, T. 2008*a*. Tectonic implications of geomorphic characterization of watersheds using spatial correlation: Mohand Ridge, NW Himalaya, India. *Zeitschrift für Geomorphologie*, **54**, 489–501.

Singh, T. 2008*b*. Hypsometric analysis of watersheds developed on actively deforming Mohand anticlinal ridge, NW Himalaya. *Geocarto International*, **23**, 417–427.

Singh, T. & Jain, V. 2009. Tectonic constraints on watershed development on frontal ridges: Mohand Ridge, NW Himalaya, India. *Geomorphology*, **106**, 231–241.

Srinagesh, D., Bhaskar, Y.V.B.S.N., Thandan Babu Naik, R., Solomon Raju, P., Sarma, A.N.S., Vijay Kumar, T. & Yedekar, D.B. 2008. *Preliminary Report on Seismic Activity at Nanded City, Maharashtra Region unpublished report submitted to District Collector*. Nanded, Govt. of Maharashtra (Unpublished report).

Srinagesh, D., Srinivas, T.V.N. *et al.* 2012. Causative fault of swarm activity in Nanded City, Maharashtra. *Current Science*, **103**, 366–369.

Srivastava, R.K. 2007. *Study of Lineament Fabric Around Nanded, Maharashtra by Remote Sensing*. Unpublished note from the Geological Survey of India, Central Region, Nagpur, India.

Tiwari, M.P. 1999. Quaternary lithostratigraphic formations of Central Indian river basin, their correlation and chronology. *Gondwana Geological Magzazine Special Publications*, **4**, 17–31.

Twidale, C.R. 2004. River patterns and their meaning. *Earth-Science Reviews*, **67**, 159–218.

Vannoli, P., Basili, R. & Valensise, G. 2004. New geomorphic evidence for anticlinal growth driven by blind-thrust faulting along the northern Marche coastal belt (central Italy). *Journal of Seismology*, **8**, 297–312.

Verrios, S., Zygouri, V. & Kokkalas, S. 2004. Morphotectonic analysis in the eliki fault Zone (Gulf of Corinth, Greece). *Bulletin of the Geological Society of Greece*, **36**, 1706–1715.

Whitney, B.B. & Hengesh, J.V. 2015. Geomorphological evidence of neotectonic deformation in the Carnarvon Basin, Western Australia. *Geomorphology*, **228**, 579–596.