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E–W strike slip shearing of Kinwat granitoid at South East Deccan Volcanic Province, Kinwat, Maharashtra, India

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We study the margin of South East Deccan Volcanic Province around Kinwat lineament, Maharashtra, India, which is NW extension of the Kaddam Fault. Structural field studies document ∼E–W strike-slip mostly brittle faults from the basement granite. We designate this as 'Western boundary East Dharwar Craton Strike-slip Zone' (WBEDCSZ). At local level, the deformation regime from Kinwat, Kaddam Fault, micro-seismically active Nanded and seismically active Killari corroborate with the nearby lineaments. Morphometric analyses suggest that the region is moderately tectonically active. The region of intense strike-slip deformation lies between seismically active fault along Tapi in NW and Bhadrachalam in the SE part of the Kaddam Fault/lineament. The WBEDCSZ with the surface evidences of faulting, presence of a major lineaments and intersection of faults could be a zone of intraplate earthquake.

Keywords. Deccan trap; brittle and ductile faulting; lineaments; tectonics.

1. Introduction

Observations of deformations in Deccan Volcanic Province (Kaplay *et al.* 2013; Misra and Mukherjee 2015; Babar *et al.* 2017; Kaplay 2017; Mukherjee *et al.* 2017) and microseismic activities (Gupta and Joshi 2001; Srinagesh *et al.* 2012; Subhadra *et al.* 2015) around Nanded (Maharashtra, India) prompted us to investigate the tectonics of the South East Deccan Volcanic Province (SEDVP). The region SE of SEDVP has tectonic imprints of Precambrian age, reactivated during Tertiary (Sangode *et al.* 2013). The faulted block west of the Kaddam Fault (KF) is tilted towards south near the Adilabad region during the Quaternary.

The Kinwat region is part of the 'South East Deccan Volcanic Province', with ancient basement granite complex. Below the Deccan trap basalts lies the granite body. Neoproterozoic Pakhal sediments overlie the Kinwat granitoids (Banerjee and Shivkumar 2010a). The Kinwat granitoids is a part of the eastern Dharwar Craton. N–S transcurrent strike slip deformation has been reported from this craton (Jayananda *et al.* 2000). Tabular- and lens-shaped mafic enclaves are usually found in the basement granites and granitoids.

These enclaves are most probably the product of magma differentiation/mixing that primarily produced granites/granitoids (Vernon 1990; Barbarin and Didier 1992). The radioactive element bearing Kinwat granitoids (Banerjee and Shivkumar 2010a) are transected by quartzofeldspathic/pegmatitic/quartz veins, chlorite and epidote veinlets and dolerite dykes. Granitic gneisses occur as the 'Kinwat inlier': a valley flat parallel to the Penganga River. The Kaddam Fault defines the southern margin of this inlier (GSI 2001). The fault plane also defines a sharp contact between granites and Deccan Trap (Banerjee and Shivkumar 2010a). The Tapi region is tectonically active. The Mw 6.F2 Satpura earthquake on 14th March 1938 (Rao 2000) reveals this. Combined with the Kinnerasani–Godavari fault, the Kinwat Lineament (KL) continues till Bhadrachalam, which is another seismic zone (Rao 2000). Geological Survey of India's seismo-tectonic atlas (2000) recognizes the Kaddam Fault to be neotectonic. Thus the Kinwat region is bound by seismically active zones, viz., Tapi towards NW and Bhadrachalam towards SE (Naganjaneyulu *et al.* 2010).

The northern part of the Kaddam mega lineament passes through the Kinwat region, which we study here and refer as the 'Kinwat Lineament'. Banerjee and Shivkumar (2010a) have mentioned cursorily tectonic reactivation in terms of fracturing and faulting from this region, which we elaborate from fieldwork and geomorphic studies. We study here the Kinwat region to document surface expression of faults, elongation ratio and asymmetric factor of the basin to understand its tectonic implication. Previous studies such as Banerjee and Shivkumar (2010b) merely referred brittle-ductile shear from Kinwat region, but neither detail/photo evidences nor any altitude data were presented.

Tectonically active-, moderately active- and inactive basins have elongation ratios <0.5, 0.5–0.75 and >0.75, respectively (Cuong and Zuchiewicz 2001). The asymmetry factor (AF) detects any regional tilt of the basin (Keller and Pinter 2002). A stream network through a stable region with uniform lithology shows AF∼50. The magnitude

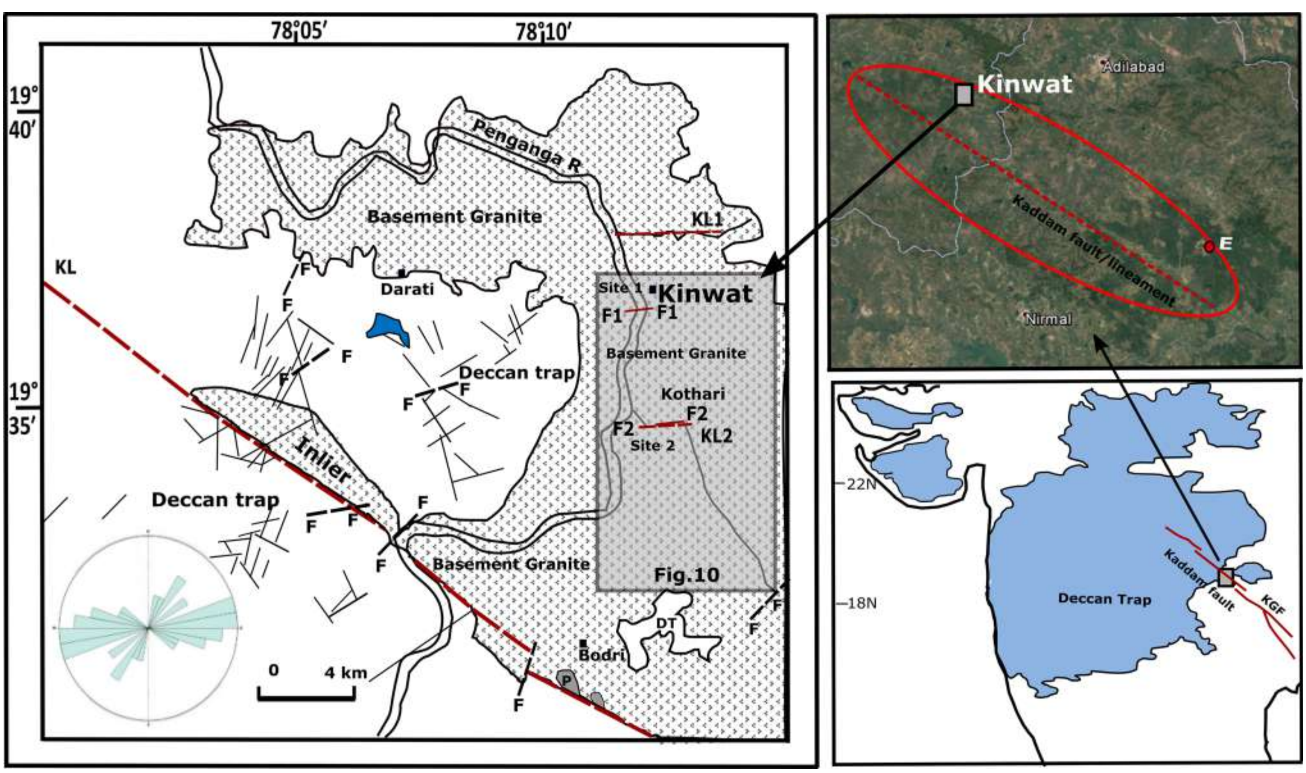

Figure 1. Location map showing the sites of preliminary investigations near Kinwat. KL1: Kinwat Lineament; KL2: Kothari Lineament. Note 'F1–F1' faults are sub-parallel to the ∼E-trending KL1 and F2–F2 are sub-parallel to the KL2. Red ellipse is the extent of the West Boundary East Dharwar Craton Strike-slip Zone (WBEDCSZ). Red dot (marked as *E*): epicenter of the recent earthquake (11 July, 2015). Rose diagram: dominant fault (Y-plane) trends documented in this study. KGF: Kinnerasani–Godavari fault; DT: Deccan trap; P: Pakhal Group; FF: faults; blue area: water body. The lithologic map is reproduced from Banerjee and Shivkumar (2010a).

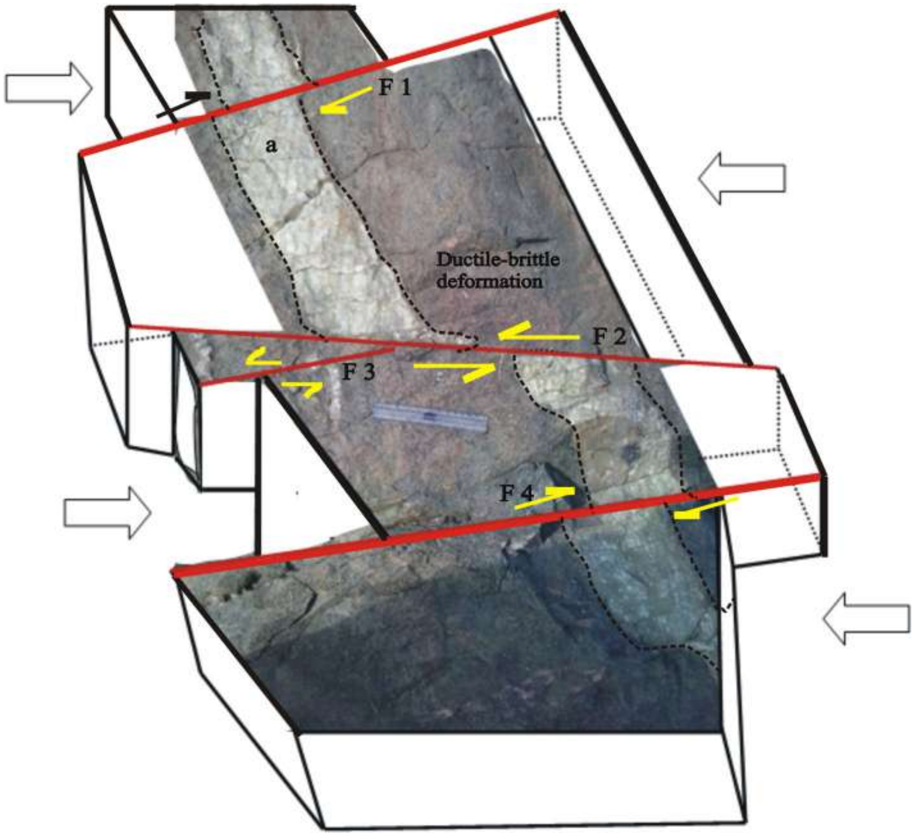

Figure 2. Quartzofeldspathic vein in granitoids showing ∼E–W strike slip faulting as observed on a near horizontal plane (at site 1, Gokunda; see figure 1 for location). 3D perspective added. Normal drag (Mukherjee and Koyi 2009; Mukherjee 2013a, 2014a, b, 2015) across some fault planes is found. The length of the scale used as a marker, is 15 cm. a: vein showing shear along boundary.

would vary for the unstable regions (Keller and Pinter 2002). The elongation ratio of Kothari Basin is determined to decipher if it is tectonically active. We also comment here the relationship between deformation and local stream orientations.

2. Present work

2.1 *Structural geology*

We chose two sites: along the Penganga River (site 1) and the Kothari lineament (site 2) (figure 1). The deformations are well preserved along the vein intrusion/mafic enclaves and granitic gneiss. Shear senses along faults is determined by kinematic indicators such as off-set of markers/enclaves/veins for more than 30 cases.

Site-1 comprises several discontinuous, mutually non-parallel sharp ∼straight ∼E-trending fault planes and mainly brittle shear zones. Figure 2 shows slip of a quartzo-feldspathic vein by four strike-slip faults presumably belonging to a single generation of deformation. They show both dextral and sinistral shear. Sharp slip without any drag (type 'b.2' flanking structure as per figure 19 of Mukherjee 2014a) indicates purely brittle deformation. Drag connoting brittle ductile deformation is also seen. Sub-parallel veins of different thicknesses side by side are brittle sheared (figures 3–5). Brittle-ductile deformation usually is considered to happen before brittle deformation, and a greater depth than the former (Mukherjee and Koyi 2010a, b). The fault plane is discontinuous in the country rock, yet they slip only the veins. Neither fault gouge nor any breccia was found. Therefore, it would be difficult to assess absolute age of faulting.

Small amphibolite veins in granitoid stretched as deciphered from normal dragged veins before breaking in a brittle way (figure 6). This indicates a ductile deformation, which was followed by a brittle deformation. The strike-slip component here is 16 cm (figure 6). Fault F_{25} is an oblique slip fault with 4.3 cm strike-slip, 1.1 cm dip-slip, and ∼4.55 cm net slip components (figure 7). The fault plane dips

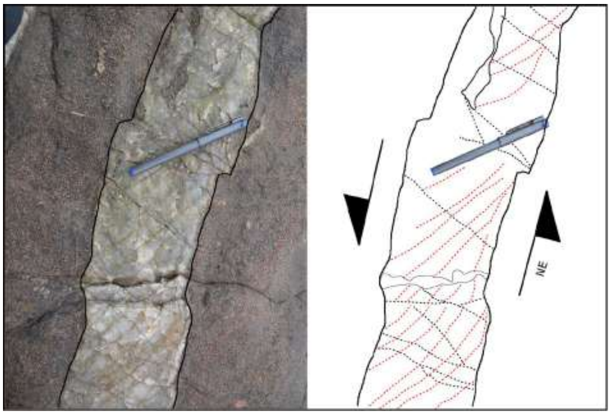

Figure 3. Quartz vein with sinistral slip (at site 1, Gokunda; see figure 1 for location) as indicated by close-spaced P shear planes (shown by red dash lines in sketch) observed on a near horizontal plane. Inclination of P planes (red dash lines in sketch) with respect to the vein margins (that acted as the Y-planes) deduce shear sense. Length of pen: 14 cm.

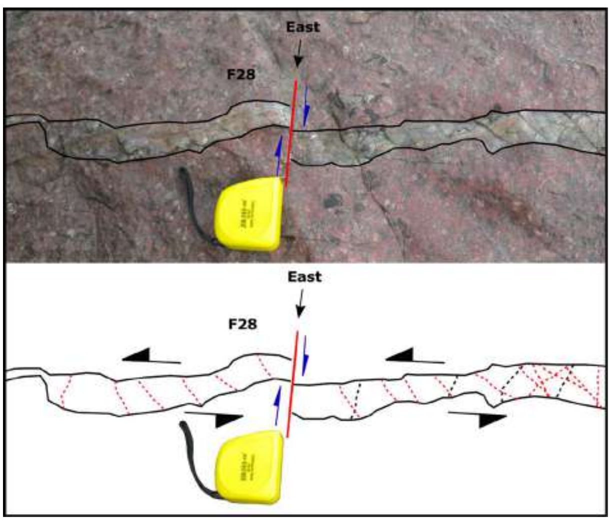

Figure 4. A brittle sheared vein got faulted. The E–W strike slip deformation postdates the shear sense indicated by P planes developed inside the quartz vein, observed on a near horizontal plane.

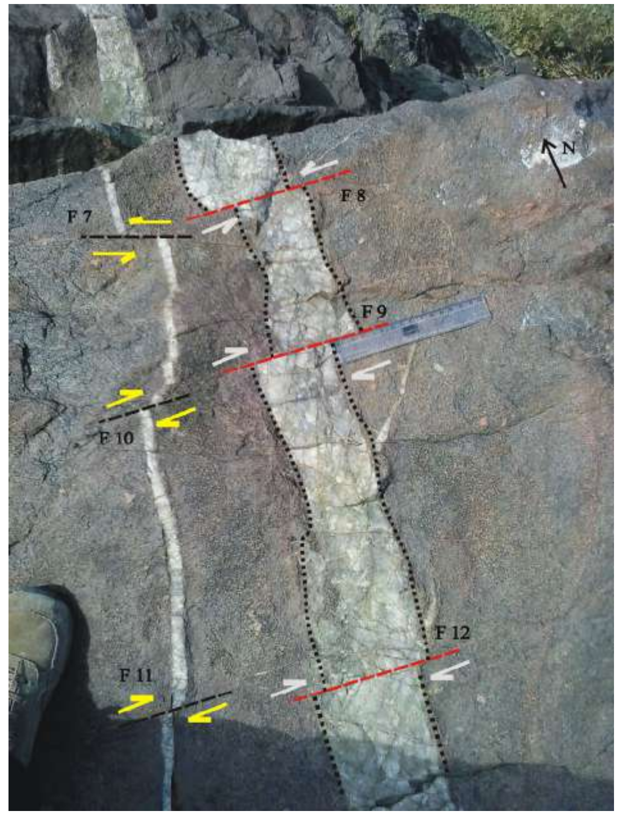

Figure 5. Quartzofeldspathic vein in granitoids shows brittle and brittle-ductile deformation, observed on a near horizontal plane. At site 1, Gokunda: see figure 1 for location. Length of scale: 15 cm.

70° due W. In another outcrop, epidote vein inside granitoid rock is strike-slip faulted with ∼6 cm slip (figure 8).

Figure 9 interestingly shows dextrally slipped basic enclave inside a thin shear zone that displaced felsic vein ductilely. The vein outside the shear zone is ∼4 cm thick, which reduces to ∼1 cm inside the shear zone. Foliations inside the shear zone parallel to the boundaries of the zone (inset of figure 9) and are much close-spaced. Table 1 presents field information acquired from fault planes. Stretching lineations were not found on the fault planes. Therefore, shear senses were deduced solely based on slip of marker layers. This is as practiced by field structural geologists (e.g., Dasgupta and Mukherjee 2017; Mukherjee 2007, 2010a, b, 2013b; Misra and Mukherjee 2017). Near consistent geographic sense of slip confirms those are not just apparent slip sense. The fault planes dip steeply or are sub-vertical. Net slip ranges 0.4–20 cm. Besides predominantly strike slip faulting, 16 sinistral and 16 dextral cases, a single case of oblique slip shear was found (table 1, figure 8, F_{25}). The region where more than one marker slipped along some fault, we got both dissimilar (sl. no. 3 in table 1) and similar (sl. no. 29 in table 1) net slips. In other words, net slip can vary along the length of the same fault (as in Johnson *et al.* 2001 from a different terrain).

We studied Google Earth images for 300 m up to 3 km long natural lineaments supplemented by ground-check, and ignored man-made features, viz., roads, railway lines, canals, etc. We focused lineaments that (possibly) control the straight courses of local streams. One significant lineament

Figure 6. Brittle-ductile sinistral shear on the E striking fault plane. Observed on a near horizontal plane. At site 1, Gokunda: see figure 1 for location. Length of pen: 14 cm.

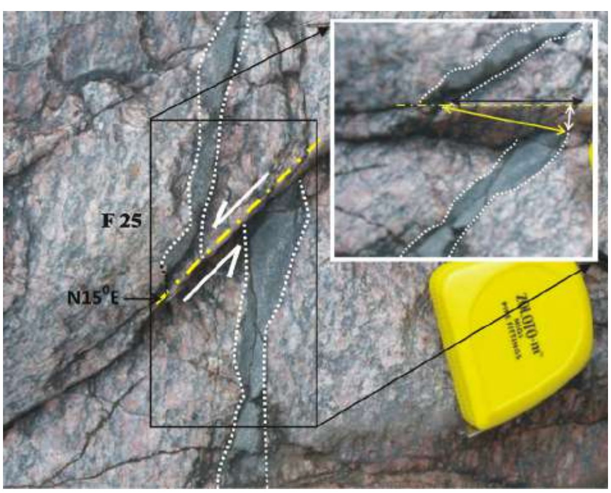

Figure 7. Basic enclave in granitic gneiss shows brittle shear (at site 1, Gokunda). Inset photograph (observation on a near vertical plane), taken from a different angle, shows the fault plane and the oblique slip more clearly.

is the ∼1136 m long 'Kothari Lineament' where a stream took a sharp turn suggesting faulting (figure 1).

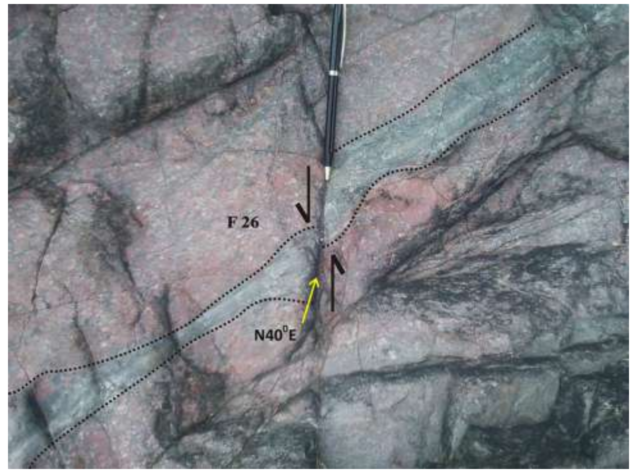

Figure 8. Epidote vein in granitic rock is dextrally strike-slip faulted, observed on a near horizontal plane. Length of pen: 14 cm.

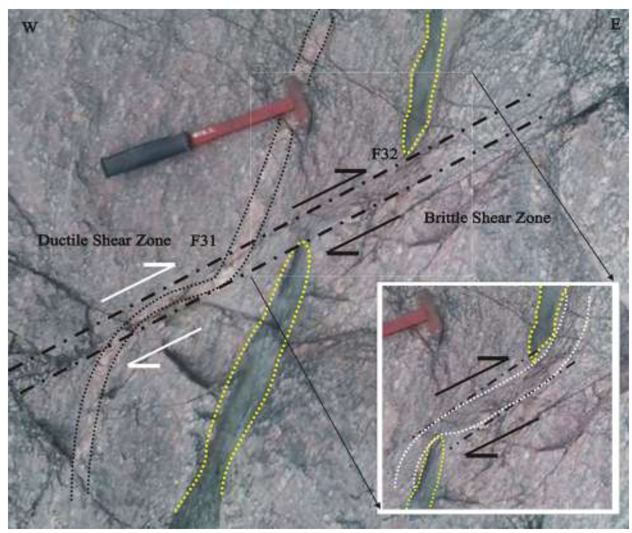

Figure 9. Basic intrusive dyke in granitic gneiss, observed on a near horizontal plane. At site 1, Gokunda.

The trends of the strike-slip faults in figures 2–4 near site 1 matches with the local lineaments/straight stream course: marked as L–L in figure 1 near Kinwat. Streams tend to follow strike slip fault planes/zones.

Rose diagram in figure 1 plots trend of faults. The dominant distribution ranges N70°−90°E (45%). The second dominant distribution ranges N70°−90°W (27%). The directions of local lineaments (LL near Kinwar and Kothari: figure 1) corroborate with the strike-fault trends.

2.2 *Geomorphologic studies*

We choose four basins (figure 10) to check whether those are tectonically active. The morphometric parameters, viz., stream order, total basin area, maximum basin length, elongation ratio and asymmetry factor of the sub-basins are estimated (table 2). The basin elongation ratio computed for the Kinwat basin is 0.65, Subhas Nagar basin is 0.65, Gokunda basin is 0.70 and Kothari basin is 0.69. These values indicate that the region is moderately to slightly tectonically active. Cuong and Zuchiewicz (2001) classified the basin settings with reference to basin elongation ratio values as slightly active basin (when Re ranges 0.50–0.75) and inactive basins (when Re >0.75), while Strahler (1964) determined Re ranges from 0.6 for tectonically active basin to 1.0 for tectonically inactive, oval to circular basins. In the present study, elongation ratio for four basins varies from 0.65 to 0.70, hence the basins are tectonically slightly active. Further, the basins in figure 10 are individual tributaries of the Penganga river for the stretch of about 10 km. Figure 10 contains small basins and it is not the entire catchment of the Penganga.

Hare and Gardner (1985) determined asymmetry factor for detecting tectonic tilt in a basin area, while Molin *et al.* (2004) observed the influence of tectonics on the drainage pattern that the asymmetry of drainage basins indicate. Asymmetry factors of the four basins range 62.2–75.91 (table 2). All the basins show the anomalous asymmetry factor indicating tectonic influence. Dominant brittle deformation in the terrain confirms this.

Nanded and its surrounding region lie in the zone III of the Indian map of seismic zonation (Subhadra *et al.* 2015). The region has experienced earthquake as early as 1942 (Valdiya 2015 and references therein). From the year 2006 onwards, microseismicity restarted (Subhadra *et al.* 2015). One of the strongest seismicity took place on 12 November, 2007 at 1.5–4 km depth by a causative fault that trends ∼SE and dips 60° (Srinagesh *et al.* 2012). Earthquake has been recorded also at 05.09 a.m. on 11 July, 2015, near the Kaddam lineament (19.251°N, 78.805°E) with 2.6 coda magnitude (figure 11), which is recorded at two of our stations located in Nanded. Using SEISAN and Hypo71 (Lienert and Havskov 1995), the event has been located with an RMS error of 0.6 s using the first polarities for the direction.

3. Discussion and conclusions

Banerjee and Shivkumar's (2010a) map shows several ∼NE and ∼NW trending lineaments from Deccan trap, west of Kinwat region but not from the Kinwat region itself. We observed that the deformation style around the eastern margin of the Deccan Volcanic Province at Kinwat does not match with those at its western margin at Nanded and Killari (figure 12). The east trending brittle shear reported here is a new addition in the tectonics of the area, to our knowledge. At Killari, the Deccan trap is ∼330 m deep (Roy and Rao 1999). Instead, the trend of the strike-slip faults with dextral and sinistral shears, devoid of gouge, breccias and secondary Riedel shears from Kinwat, match with ∼E–W Kothari Lineament (figure 1). The observed ductile-, brittle-ductile and brittle shear happened presumably at >8–15 km, ∼8–15 km, and <8–15 km depths, respectively (Passchier and Trouw 2005). Ductile shears are much less numerous than the other two types. Lack of crosscutting relation between the thrusts and strike slip faults make it difficult to comment on their relative timing. Also, lack of fault gouge would make it difficult to estimate absolute timing of the fault slips. Geomorphologic parameters estimated in this study indicate that the Kinwat region is tectonically active today. Interestingly, the nearby region: the Asna–Godavari basins too is tectonically active (Babar *et al.* 2011). An ∼E-trending strike slip fault plane would indicate, as per Anderson's model (Anderson 1905), either a ∼ENE or a ∼WNW trending maximum principal stress direction. This can be reached by presuming the possible conjugate strike slip fault at either side of the ∼E-trending fault plane. We also note that the strike-slip faults reported near Kaddam lineament trend NW which match the trend of the Kaddam fault. The micro-seismically active Nanded is covered by the Deccan basalt, which is ∼100 km SW of Kinwat. Surface manifestation of compressional structures has been reported so far from few Large Igneous Provinces (review in Ernst 2014) but those have been very sparse in the Deccan trap. For example, Kaplay *et al.* (2013) reported NW-trending causative thrust fault, which is a compressional structure. In addition, Madhnure (2014) reported NE-trending lineaments from Nanded (that are productive for groundwater exploration). Local compressional structures might be produced by regional domal uprise (Mukherjee *et al.* 2012) of such igneous terrains, coeval to the ongoing strike slip shear, but the detail and actual mechanism have remained indeterminate (review in Ernst 2014). No fault has so far been reported from surface at Killari (Kayal 2007, 2010). An oblique

Table 1. *Trends and shear senses of slip faults found in this study from Gorakshan (see figure 1 for location).*

Sl. no.	Structure no.	Deformation regime	Type of fault	Shear sense	Strike	Net slip (cm)
1	F_1	BD	Strike slip	Dextral	N74°E	1
2	F_2	BD	Strike slip	Sinistral	N80°W	19
3	F_3	B	Strike slip	Sinistral	N80°E	14, 2
4	F_4	B	Strike slip	Dextral	N83°E	5
5	F_5	B	Strike slip	Dextral	E–W	2
6	F_6	BD	Strike slip	Sinistral	N58°W	9
7	F_7	B	Strike slip	Sinistral	E–W	3
8	F_8	BD	Strike slip	Sinistral	N75°E	4
9	F_9	B	Strike slip	Dextral	N75°E	3
10	F_{10}	BD	Strike-Slip Fault	Dextral	N79°E	1
11	F_{11}	B	Strike slip	Dextral	N79°E	1.1
12	F_{12}	B	Strike slip	Dextral	N79°E	1.1
13	F_{13}	BD	Strike slip	Sinistral	E–W	16
14	F_{14}	B	Strike slip	Sinistral	N40°E	2
15	F_{15}	B	Oblique slip	Sinistral	N15°E	2.5
16	F_{16}	BD	Strike slip	Sinistral	N80°E	3.5
17	F_{17}	B	Strike slip	Dextral	N74°W	5
18	F_{18}	B	Strike slip	Sinistral	N74°W	6
19	F_{19}	B	Strike slip	Dextral	N84°W	3
20	F_{20}	BD	Strike slip	Dextral	N55°E	5
21	F_{21}	B	Strike slip	Sinistral	N77°W	3
22	F_{22}	B	Strike slip	Dextral	N52°E	2
23	F_{23}	B	Strike slip	Sinistral	N82°W	4
24	F_{24}	B	Strike slip	Sinistral	N80°W	3
25	F_{25}	B	Strike-Slip Fault	Sinistral	N63°W	2
26	F_{26}	B	Strike-Slip Fault	Dextral	N82°E–S82°W	2
27	F_{27}	B	Strike slip	Dextral	N82°E	2.2
28	F_{28}	B	Strike slip	Dextral	E–W	1.1
29	F_{29}	B	Strike slip	Dextral	N80°W	0.6, 0.4
30	F_{30}	B	Strike slip	Sinistral	N20°E	3
31	F_{31}	B	Strike slip	Dextral	N35°E	20
32	F_{32}	D	Strike slip	Dextral	N35°E	24
33	F_{33}	D	Strike slip	Sinistral	N35°E	12

B: Brittle; BD: Brittle ductile; D: Ductile.

slip faulting reported in this work (sl. no. 15 in table 1) along with the blind thrusts (e.g., at Killari) supplemented by outward river courses near the margin of the Deccan trap (reviewed in Ernst 2014) indicate a possible domal uplift of the Deccan volcanics. At shallow crustal level, there could be oblique slip faults along with thrust components. However, a domal uplift of the Deccan trap (Ernst 2014) possibly cannot facilitate a strike slip shear at its periphery and inside the basement rocks.

The Latur region (Gujarat, India) is covered by 300–500 m thick Deccan trap (Chetty 2006). The trap thins towards East (Patro and Sarma 2007). Faults are reported from ∼500 m thick Deccan Volcanic Province near the Kurduwadi Lineament, and near Killari where the trap is ∼400 m thick. In north Nanded, thrusts are reported from ∼200 m thick Deccan Volcanic Province. Deccan Volcanic Province thins from Kurduwadi to Kinwat. Faults at Killari and Nanded may have continued into the underlying Archean/Precambrian crustal granites. The strike-slip faults in the present study are reported from this granitic crust.

Around 6-km long Tirna Tributary Lineament near Killari, the Urvashi Ghat (UG) Lineament of similar length near Nanded, ∼15 km long Kinwat Lineament, near Kinwat and Kaddam Lineament, all trend ∼NW (figure 12).

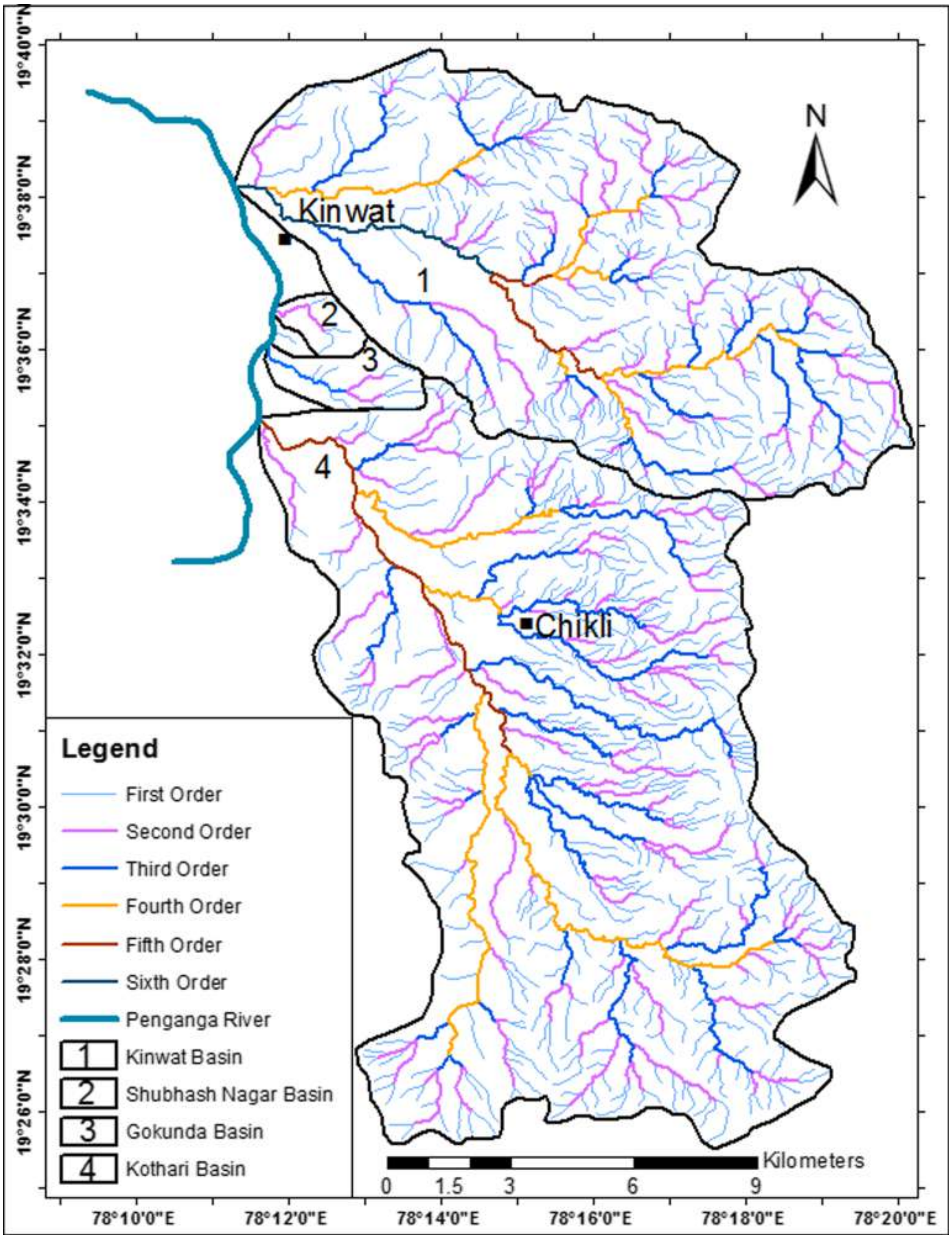

Figure 10. Drainage map of the four basins.

We do not link the observed deformation with post-Deccan trap isostatic adjustment (Srinivasan 2002; Mall *et al.* 2005) as that would require vertical slip, which we did not observe. Since our observed brittle planes are not just fracture planes, we do not link them with post Deccan fracturing of Peshwa *et al.* (1987). Eastern part of Deccan trap has revealed NE-trending post-Deccan normal faults based on stratigraphic studies (Shrivastava and Pattanayak 1999). As we did not note normal faults in the present study, we cannot link the observed fault planes with them.

Misra *et al.* (2014) documented from field ∼N-trending strike slip faults in and around Mumbai (Indian west coast; also see Misra *et al.* 2015; Misra and Mukherjee 2017). The E-trending faults reported here and those trending N (Misra *et al.* 2014) cannot be 'conjugated'/genetically linked/coeval. This is because, (i) they are near orthogonal unlike acute angle as predicted in Anderson's model (Fossen 2016), and (ii) they do

Table 2. *Morphometric parameters of the four basins.*

Sl. no.	Morphometric parameters	Kinwat sub-basin	Subhash Nagar basin	Gokunda basin	Kothari basin
1	Stream order of major stream	6th	6th	2nd	5th
2	Area (A) (km^2)	101.19	97.32	1.80	163.20
3	Maximum basin length (L) (km)	17.59	17.37	2.15	20.89
4	Elongation ratio (Re) $Re = (\frac{2\sqrt{A}/\sqrt{\pi}}{L})$ (unitless)	0.65	0.65	0.70	0.69
5	Asymmetry factor (AF) AF = 100(Ar/At) (unitless) Ar: Area of the basin to the right of facing downstream stream At: Total area of the basin	64.81	64.30	62.2	75.91

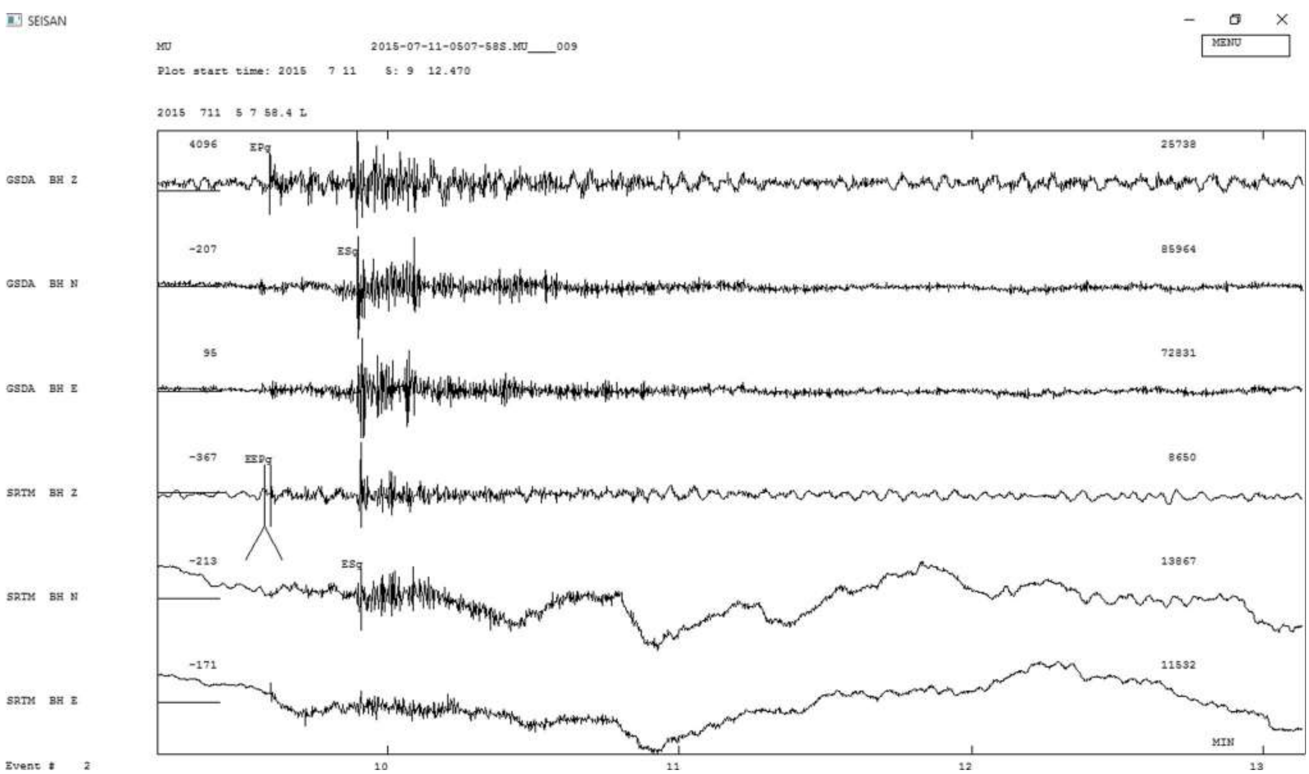

Figure 11. Record of seismicity near the Kaddam Lineament (refer figure 1 for location) recorded at Nanded (X-axis: minutes; Y-axis: amplitude).

not occur side by side. The easternmost exposure of ∼N-trending fault at Malshej Ghat in Misra *et al.* (2014) is ∼780 km W of Kinwat.

Mandal and Singh's (1996) estimated stress distribution restricts at the western part of the Deccan trap, and probably cannot be extended for the eastern region such as Nanded. Mandal *et al.* (1997), on the other hand, deciphered strike slip tectonics from seismic studies at ∼7 km depth from Killari, which is ∼108 km away from Nanded. They estimated a maximum principal stress of 20.5 MPa at 50 km SSW of Nanded. The ∼E-trending brittle slip we observe here could be a surface manifestation of this stress produced by doming of the Deccan trap that could affect the surrounding rocks as well. The possible tectonic relation between Tapi rift and the lineaments referred in this work could be a topic of further

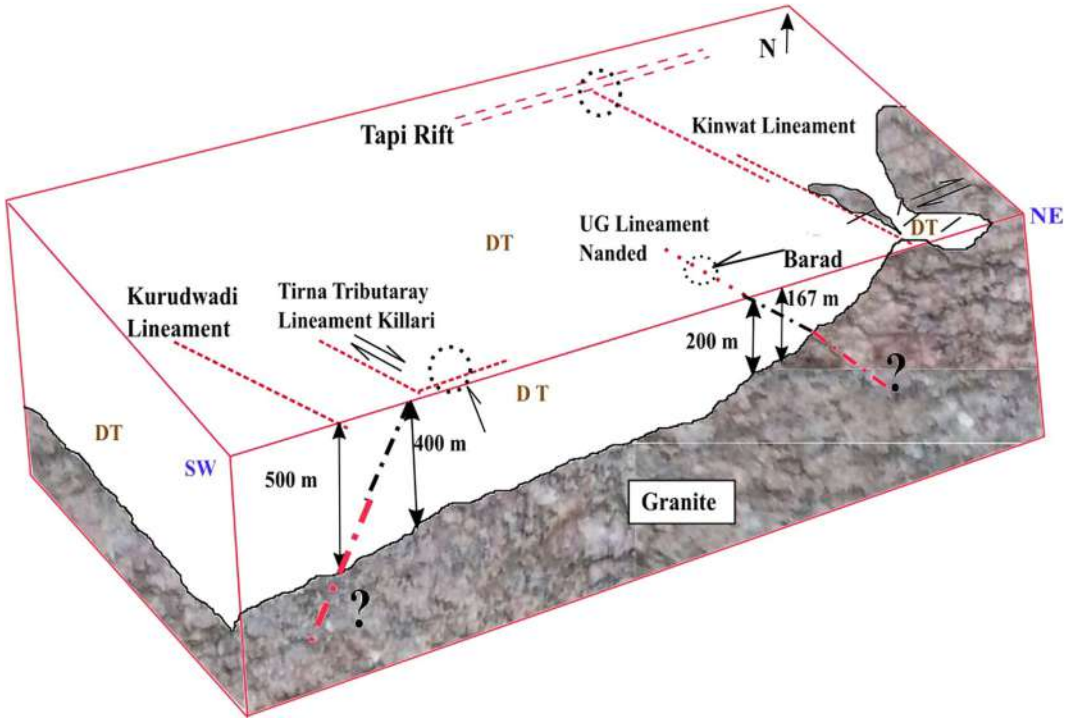

Figure 12. 3D cartoon: probable occurrence of faults in basement granite at Kurudwadi, Killari and Nanded. It also shows progressively thinning of Deccan Trap (DT) towards E (based on Chetty 2006; Patro and Sarma 2007; Harinaryana *et al.* 2007). Dotted circle: seismic zone.

research. Geophysical studies on blind faults can provide new tectonic information from the study area.

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References

Anderson E M 1905 The dynamics of faulting; *Trans. Edinb. Geol. Soc.* **8** 387–402.

Babar M D, Ghute B B and Chunchekar R V 2011 Geomorphic indicators of neotectonics from the Deccan Basaltic Province: A study from the Upper Godavari River Basin, Maharashtra, India; *Int. J. Earth Sci. Eng.* **4** 297–308.

Babar Md, Kaplay R D, Mukherjee S and Kulkarni P S 2017 Evidences of deformation of dykes from Central Deccan Volcanic Province, Aurangabad, Maharashtra, India; In: Tectonics of the Deccan Large Igneous Province (eds) Mukherjee S, Misra A A, Calvès G and Nemčok M, *Geol. Soc. London Spec. Publ.*, doi: 10.1144/SP445.13

Banerjee R and Shivkumar K 2010a Geochemistry and petrogenesis of radioactive Palaeoproterozoic granitoids of Kinwat crystalline inlier, Nanded and Yeotmal districts, Maharashtra; *J. Geol. Soc. India* **75** 596–617.

Banerjee R and Shivkumar K 2010b Petromineralogy and ore mineral paragenesis of radioactive palaeoproterozoic granitoids, Nanded District, Maharashtra, India; *Ind. Mineral.* **44** 59–73.

Barbarin B and Didier J 1992 Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas; *Earth Environ. Sci. Trans. Roy. Soc. Edinb.* **83** 145–153, doi: 10.1017/S0263593300007835.

Chetty T R K 2006 Contrasting deformational systems and associated seismic patterns in Precambrian peninsular India; *Curr. Sci.* **90** 942–951.

Cuong N Q and Zuchiewicz W A 2001 Morphotectonic properties of the Lo river fault near Tam Dao in North Vietnam; *Nat. Hazards Earth Syst. Sci.* **1** 15–22.

Dasgupta S and Mukherjee S 2017 Brittle shear tectonics in a narrow continental rift: Asymmetric non-volcanic Barmer basin (Rajasthan, India); *J. Geol.* (in press).

Ernst R E 2014 *Large Igneous Provinces*; Cambridge University Press, Cambridge, 653p.

Fossen H 2016 *Structural Geology;* 2nd edn, Cambridge University Press, Cambridge.

Geological Survey of India 2000 *Seismotectonic Atlas of India and its Environs*; Geological Survey of India.

Geological Survey of India 2001 *District resource map of Nanded district, Maharashtra, on 1:300,000 scale with explanatory brochure.*

Gupta I D and Joshi R G 2001 *Probablistic seismic zoning of Maharashtra state*; Workshop on seismicity of western

India with special reference to recent Kutch earthquake, CDAC, Pune.

Hare P H and Gardner T W 1985 Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya peninsula, Costa Rica; In: *Tectonic Geomorphology* (eds) Morisawa M and Hack J T, Allen and Unwin, Boston, pp. 75–104.

Harinaryana T, Patro B P K, Veeraswamy K, Manoj C, Naganjaneyulu K, Murthy D N and Voripakshi G 2007 Regional geoelectric structure beneath Deccan Volcanic Province of the Indian subcontinent using magnetotellurics; *Tectonophys.* **445** 66–80.

Jayananda M, Moyen J-F, Martin H, Peucat J-J, Auvray B and Mahabaleswar B 2000 Late Archaean (2550–2520 Ma) juvenile magmatism in the Eastern Dharwar craton, southern India: Constraints from geochronology, Nd–Sr isotopes and whole rock geochemistry; *Precamb. Res.* **99** 225–254.

Johnson K M, Hsu Y-J, Segall P and Yu S B 2001 Fault geometry and slip distribution of the 1999 Chi-Chi, Taiwan earthquake imaged from inversion of GPS data; *Geophys. Res. Lett.* **28** 2285–2288.

Kaplay R D, Babar Md, Mukherjee S and Kumar T V 2017 Morphotectonic expression of geological structures in eastern part of south east Deccan volcanic province (around Nanded, Maharashtra, India); In: Tectonics of the Deccan Large Igneous Province, *Geol. Soc. London, Spec. Publ.*, doi: 10.1144/SP445.12.

Kaplay R D, Vijay Kumar T and Sawant R 2013 Field evidence for deformation in Deccan Traps in microseismically active Nanded area, Maharashtra; *Curr. Sci.* **105** 1051–1052.

Kayal J R 2007 *Recent Large Earthquakes in India: Seismotectonic Perspective*; *IAGR Memoir* **10** 189–199.

Kayal J R 2010 *Microearthquake Seismology and Seismotectonics of South Asia*; Springer, 503p.

Keller E A and Pinter N 2002 *Active tectonics: Earthquakes, uplift, and landscape;* 2nd edn, Prentice Hall, ISBN-13: 978-0130882301.

Lienert B R and Havskov J 1995 A computer program for locating earthquake both locally and globally; *Seismol. Res. Lett.* **66** 26–36.

Madhnure P 2014 Groundwater exploration and drilling problems encountered in basaltic and granitic terrain of Nanded District, Maharashtra; *J. Geol. Soc. India* **84** 341–351.

Mall D M, Singh A P and Sarkar D 2005 Structure and seismotectonics of Satpura, central India; *Curr. Sci.* **88** 1621–1627.

Mandal P, Manglik A and Singh R N 1997 Intraplate stress distribution induced by topography and crustal density heterogeneities beneath the Killart, India region; *J. Geophys. Res.* **102** 11,719–11,729.

Mandal P and Singh R N 1996 Three-dimensional intraplate stress distributions associated with topography and crustal density inhomogeneities beneath the Deccan Volcanic Province; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **105** 143–155.

Misra A A, Bhattacharaya G, Mukherjee S and Bose N 2014 Near N–S paleo-extension in the western Deccan region, India: Does it link strike-slip tectonics with India–Seychelles rifting? *Int. J. Earth Sci.* **103** 1645–1680.

Misra A A and Mukherjee S 2015 *Tectonic Inheritance in Continental Rifts and Passive Margins*; Springer Briefs in Earth Sciences.

Misra A A and Mukherjee S 2017 Dyke-brittle shear relationships in the Western Deccan Strike Slip Zone around Mumbai (Maharashtra, India); In: Tectonics of the Deccan Large Igneous Province, *Geol. Soc. London, Spec. Publ.* **445** 269–295, doi: 10.1144/SP445.4.

Misra A A, Sinha N and Mukherjee S 2015 Repeat ridge jumps and microcontinent separation: Insights from NE Arabian Sea; *Mar. Petrol. Geol.* **59** 406–428.

Molin P, Pazzaglia F J and Dramis F 2004 Geomorphic expression of active tectonics in a rapidly-deforming forearc, Sila Massif, Calabria, southern Italy; *Am. J. Sci.* **304** 559–589.

Mukherjee S 2007 Geodynamics, deformation and mathematical analysis of metamorphic belts of the NW Himalaya; Ph.D. thesis, Indian Institute of Technology Roorkee, 267p.

Mukherjee S 2010a Structures in meso- and micro-scales in the Sutlej section of the Higher Himalayan Shear Zone, Indian Himalaya; *e-Terra* **7** 1–27.

Mukherjee S 2010b Microstructures of the Zanskar Shear Zone; *Earth Sci. India* **3** 9–27.

Mukherjee S 2013a *Deformation Microstructures in Rocks;* Springer Geochemistry/Mineralogy, Berlin, 111p.

Mukherjee S 2013b Higher Himalaya in the Bhagirathi section (NW Himalaya, India): Its structures, backthrusts and extrusion mechanism by both channel flow and critical taper mechanisms; *Int. J. Earth Sci.* **102** 1851–1870.

Mukherjee S 2014a Review of flanking structures in meso- and micro-scales; *Geol. Mag.* **151** 957–974.

Mukherjee S 2014b *Atlas of Shear Zone Structures in Meso-scale;* Springer Geology Cham., 124p.

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

Mukherjee S, Misra A A, Calvès G and Nemčok M 2017 Tectonics of the Deccan large igneous province: An introduction; In: Tectonics of the Deccan Large Igneous Province (eds) Mukherjee S, Misra A A, Calvès G and Nemčok M, *Geol. Soc. London Spec. Publ.* **445**. doi: 10.1144/SP445.14.

Mukherjee S and Koyi H A 2009 Flanking microstructures; *Geol. Mag.* **146** 517–526.

Mukherjee S and Koyi H A 2010a Higher Himalayan shear zone, Sutlej section-structural geology and extrusion mechanism by various combinations of simple shear, pure shear and channel flow in shifting modes; *Int. J. Earth Sci.* **99** 1267–1303.

Mukherjee S and Koyi H A 2010b Higher Himalayan shear zone, Zanskar section – microstructural studies and extrusion mechanism by a combination of simple shear and channel flow; *Int. J. Earth Sci.* **99** 1083–1110.

Mukherjee S, Koyi H A and Talbot C J 2012 Implications of channel flow analogue models in extrusion of the Higher Himalayan shear zone with special reference to the out-of-sequence thrusting; *Int. J. Earth Sci.* **101** 253–272.

Naganjaneyulu K, Dhanunjayanaidu G, Someswararao M, Ravishankar K, Kishore S R K, Murthy D N, Veeraswamy K and Harinarayana A T 2010 Deep crustal electromagnetic structure of central India tectonic zone and its implications; *Phys. Earth Planet. Inter.* **181** 60–68.

Passchier C W and Trouw R A J 2005 *Microtectonics*; 2nd edn, Springer, Heidelberg.

Patro B P K and Sarma S V S 2007 Trap thickness and the subtrappean structures related to mode of eruption in the Deccan Plateau of India: Results from magnetotellurics; *Earth Planets Space* **59** 75–81.

Peshwa V V, Mulay J G and Kale V S 1987 Fracture zones in the Deccan traps of western and central India: A study based on remote sensing techniques; *J. Ind. Soc. Remote Sens.* **15** 9–17.

Rao B R 2000 Historical seismicity and deformation rates in the Indian peninsular shield; *J. Seismol.* **4** 247–258.

Roy S and Rao R U M 1999 Geothermal investigations in the 1993 Latur earthquake area, Deccan Volcanic Province, India; *Tectonophys.* **306** 237–252.

Sangode S J, Mesharm D C, Kulkarni Y R, Gudadhe S S, Malpe D B and Herlekar M A 2013 Neotectonic response of the Godavari and Kaddam Rivers in Andhra Pradesh, India: Implications to Quaternary reactivation of old fracture system; *J. Geol. Soc. India* **81** 459–471.

Shrivastava J P and Pattanayak S K 1999 Petrochemical studies on the epicentral region of the recent Jabalpur earthquake. *Curr. Sci.* **77** 1100–1104.

Srinagesh D, Srinivas T V N, Solomon Raju P, Suresh G, Murthy Y V V B S N, Saha S, Sarma A N S and Vijay Kumar T 2012 Causative fault of swarm activity in Nanded City, Maharashtra; *Curr. Sci.* **103** 366–369.

Srinivasan V 2002 Post-Deccan trap faulting in Raigad and Thane districts of Maharashtra; *J. Geol. Soc. India* **59** 23–31.

Strahler A N 1964 Quantitative geomorphology of drainage basin and channel networks; In: *Handbook of Applied Hydrology* (ed.) Chow V T, Mac-Graw Hill, New York, pp. 4.39–4.76.

Subhadra N, Padhy S, Prabhakara P P and Seshunarayana T 2015 Site-specific ground motion simulation and seismic response analysis for microzonation of Nanded City, India; *Nat. Hazards* **78** 915–938.

Valdiya K S 2015 *The Making of India: Geodynamic Evolution*, Springer.

Vernon R H 1990 Crystallization and hybridism in microgranitoid enclave magmas: Microstructural evidence; *J. Geophys. Res.* **95** 17,849–17,859.

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