Seismotectonic implications of Delhi region through fault plane solutions of some recent earthquakes

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The present communication presents fault plane solutions of 19 earthquake events ($M_L \geq 3.0$) located in Delhi and its environs in the Delhi Fold Belt (DFB), recorded by 16-elements Seismic VSAT Telemetry Network in and around Delhi established by India Meteorological Department. The fault plane solutions based on *P*-wave polarity demonstrate that earthquakes in the DFB have a dominant mechanism of thrusting with minor strike-slip components; the nodal planes conform to (i) the Mahendragarh–Dehradun Subsurface Fault trending NNE–SSW and (ii) the Delhi–Sargodha Ridge, trending NW–SE. This communication further analyses seismotectonics of DFB vis-à-vis seismicity pattern.

Keywords: *b*-value, fault plane solutions, seismicity, seismotectonics.

THE National Capital Territory (NCT) of Delhi (area ≈1438 sq. km) is located in the Delhi Fold Belt (DFB) characterized by folded sequences of quartzite with minor meta-pellites, with distinct folding episodes of the Proterozoic period. The DFB is bounded by two important strike-slip faults, viz. the Mahendragarh–Dehradun Subsurface Fault (MDSSF) and the Great Boundary Fault (GBF). Another important structural element of the belt is the NW–SE trending Delhi–Sargodha Ridge (DSR) which passes through Delhi and is flanked by basins on either side, viz. the Sahaspur Basin in the north and the Bikaner Basin in the southwest (Figure 1). Though the epicentral location of the historical event of 1720 is debatable, macroseismic records from the annals of history confirm its location in the DSR zone[1]. Therefore, the DSR is another zone of seismotectonic importance in the context to seismic hazard of Delhi. The structural ramp of DFB is juxtaposed to the Himalayan Frontal Fold Belt[1].

Seismic hazard of NCT Delhi is a point of great concern. The potential seismic hazard in the area is attributed to the Himalayan thrust system and activation of fault systems of the DFB. The former has drawn great attention and is deliberated by the Indian as well as international scientific community[2–5]. However, consequences of earthquakes endemic to the DFB have not been analysed for paucity of sufficient data.

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The India Meteorological Department (IMD), the nodal agency of the Government of India for seismology-related matters, maintains a national seismological network of 51 observatories for monitoring seismic activity in and around the country. In 2000–01, IMD established a permanent long aperture (≈250 km), 16-elements Seismic VSAT Telemetry Network in and around Delhi for close monitoring of seismic activity in the region. It is important to note that this network has a array of nine stations with good azimuthal coverage spread in a radius of 80 km around Delhi (Figure 2). Using Hypocenter 3.2 under the SEISAN[6] analysis software, a total of 288 events were located (ERH and ERZ ≤ 4.0 km, rms < 0.9) in Delhi and its environs (lat. 28–29.75°N and long. 76–78°E) during 2001–04. Among these, only 19 events were of magnitude $M_L \geq 3.0$. This communication analyses the seismicity pattern in general and discusses focal mechanism solutions of these events having $M_L \geq 3.0$ (Table 1) through *P*-wave polarity recorded by the network. The mechanisms are related to the seismotectonic features of the area.

Delhi lies in Seismic Zone IV (BIS IS 1893, Part 1 : 2002). The city and its environs have been damaged by earthquakes from far field seismic source in the Himalaya (the Great Kangra earthquake, *M*: 8.0, 1905, IX and the Chamoli earthquake, *M*: 6.8, 1999). In addition, the Delhi domain has also been affected by earthquakes of the peninsular domain (historical earthquake of Delhi, *M*: 6.5, 1720; Mathura earthquake, *M*: 6.8, 1803; Bulandshahar earthquake, *M*: 6.7, 1956, and Faridabad earthquake, *M*: 6.0, 1960).

The northwestern part of Delhi ambience witnessed swarm activity in the Sonipat area during 1963–65. The spatial distribution of seismicity based on these data showed seismic activity concentration at three different regions, namely west of Delhi, near Sonipat and close to Rohtak, indicating extension and trends of faults buried under thick alluvium deposits[7]. Another swarm-type activity was also witnessed in Jind area (northwest of Delhi) during the period December 2003–January 2004. A total of 62 shallow focused microtremors were located and their spatial distribution showed clustering in two zones in Jind area[8]. A closer examination of clusters of these events showed that this swarm activity was related to the DSR zone.

During the period 2001–04, 288 events have been located by the Seismic Telemetry Network of IMD in the studied region. Of these, more than 90% of the events had magnitude less than 3.0, with shallow focal depth (≤15 km). The yearly energy released from 2001 to 2004 was 12.6×10^{10}, 5.01×10^{10}, 6.31×10^{10} and 7.08×10^{10} J respectively.

Spatial distribution of the epicentre showed a pattern conformable to the tectonic framework of the area. During the period of observations about 50% of the events was proximal to the trace of MDSSF, whereas about 74%

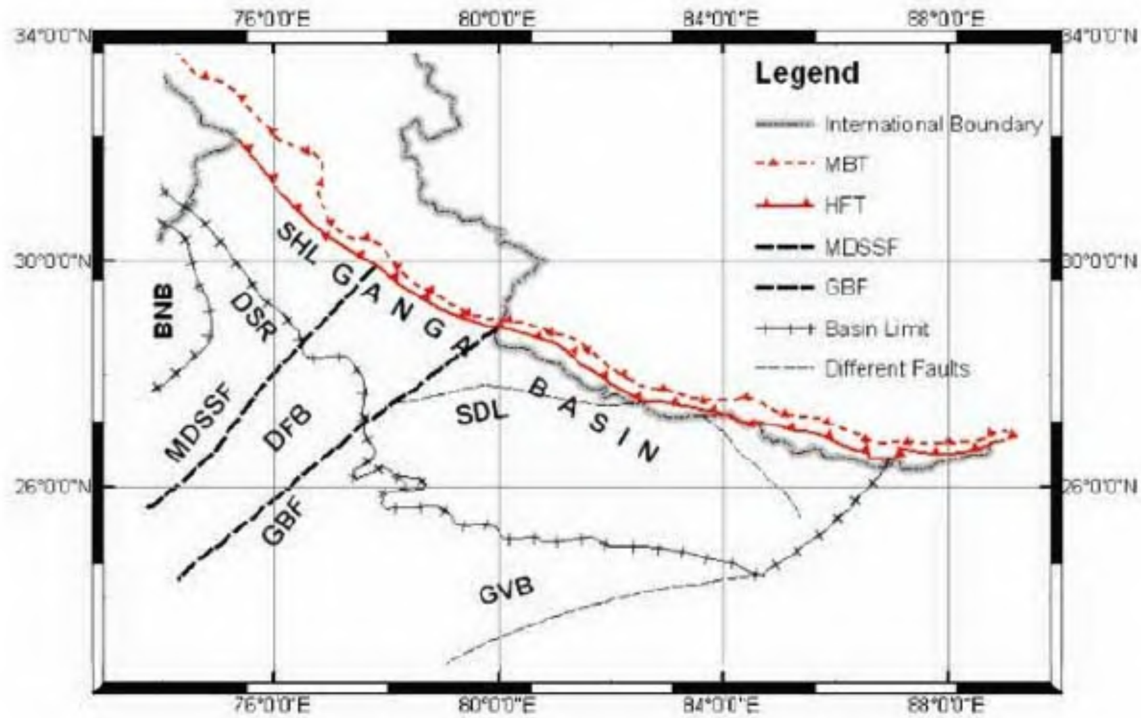

Figure 1. Tectonic framework map of Himalayan Thrust Fold Belt and foredeep: Ganga Basin (from Srinivasan and Khar[12]). HFT, Himalayan Frontal Thrust Fold Belt; MBT, Main Boundary Thrust; MDSSF, Mahendragarh–Dehradun Subsurface Fault; GBF, Great Boundary Fault; DSR, Delhi Sargodha Ridge; BNB, Bikaner Nagaur Basin; SHL, Sahaspur Low; SDL, Sarda Low; DFB, Aravali Delhi Fold Belt; GVB, Great Vindyan Basin.

Table 1. Earthquakes ($M_L \geq 3.0$) in the grid lat. 28–29.75°N, long. 76–78°E for the period 2001–04

Events	Date (yyyy mm dd)	Location			M_L
		Latitude (°N)	Longitude (°E)	Depth (km)	
1	2001 02 28	28.559	76.188	30.0	4.2
2	2001 04 28	28.557	77.090	4.1	3.8
3	2001 05 17	28.946	76.793	24.7	3.2
4	2001 07 07	29.468	77.686	15.1	3.3
5	2001 08 10	28.903	77.192	13.2	3.2
6	2001 09 12	28.684	76.511	15.0	3.4
7	2001 10 20	29.248	77.239	24.4	3.3
8	2002 05 10	28.920	76.679	14.9	3.0
9	2002 05 13	29.293	77.277	11.9	3.1
10	2002 06 19	29.235	76.466	13.7	3.5
11	2002 12 15	28.932	76.782	10.0	3.2
12	2003 04 02	29.025	76.612	15.0	3.1
13	2003 04 09	28.406	77.401	18.0	3.4
14	2003 06 16	28.420	77.435	15.1	3.1
15	2003 08 28	29.115	76.640	07.4	3.5
16	2003 09 13	29.021	76.707	05.0	3.4
17	2003 12 22	29.223	76.414	07.3	3.4
18	2004 03 17	28.957	76.889	14.2	3.2
19	2004 07 27	28.943	76.617	12.9	3.9

showed clustering in the NW–SE direction, coincident with DSR trend (Figure 3*a*). The moment release of events clustered along MDSSF and DSR was of the order of 6.5×10^{22} and 3.75×10^{22} Nm respectively, indicating that seismic activity along the MDSSF is more than that along the DSR.

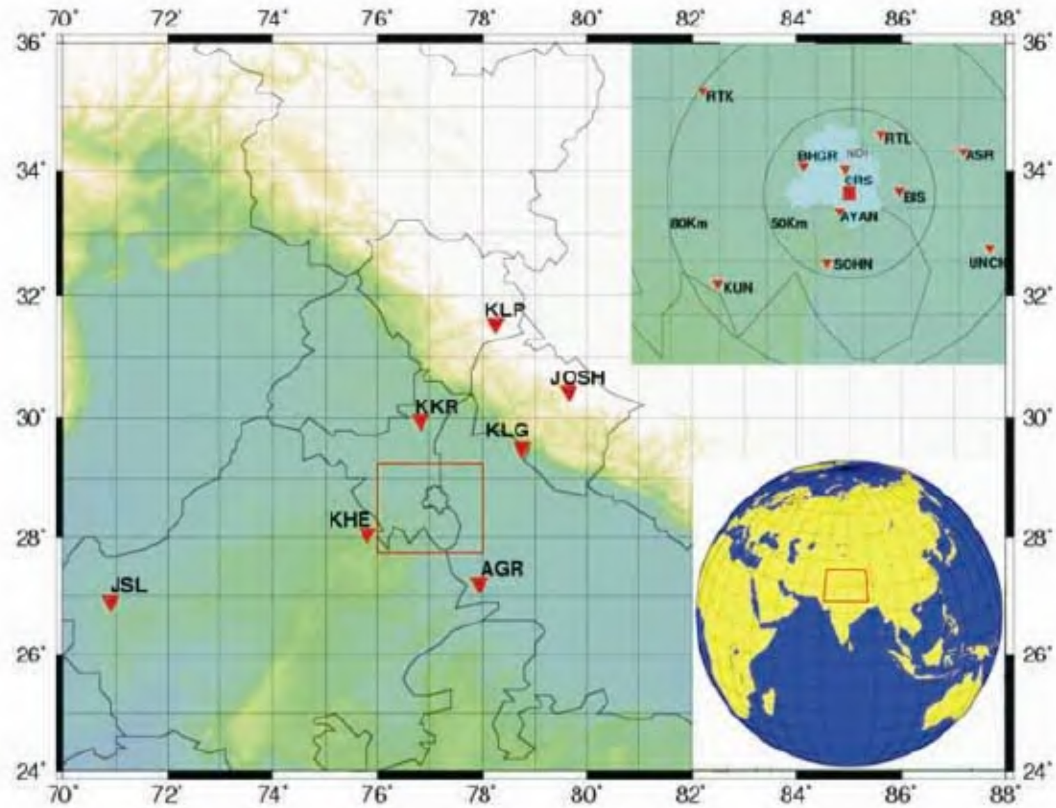

Figure 2. Sixteen elements, wide aperture (≈250 km) Seismic VSAT Telemetry Network around Delhi with close-up view of array in NCR domain. AGR, Agra; ASR, Asauara; AYAN, Ayanagar; BHGR, Bhadurgarh; BIS, Bisrakh; JOSH, Joshimath; JSL, Jaisalmer; KHE, Khetri; KKR, Kurukshetra; KLG, Kalagarh; KLP, Kalpa; KUN, Kuldal; RTK, Rohtak; RTL, Rataul; SOHN, Sohana; UNCH, Unchagaon; NDI, New Delhi Ridge; CRS, Central Receiving Station.

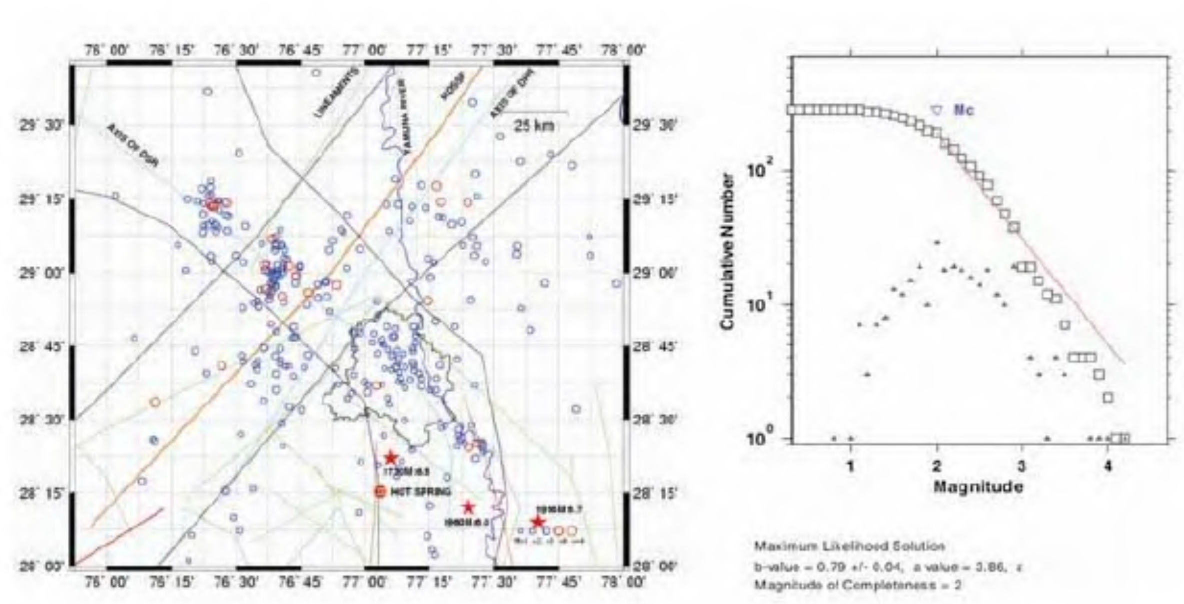

Figure 3. ***a***, Spatial distribution of events (2001–04). ***b***, *b*-value. Small triangles represent the derivative of frequency–magnitude distribution, which is used to compute the magnitude of completeness (M_c). Squares represent the cumulative number of earthquakes of a given magnitude and the straight line is the weighted least-square fit to data.

During 19 December 2003 to 31 January 2004, a swarm-type activity around Jind was observed and monitored by IMD, establishing a local network of six stations. The swarm was characterized by 152 tremors, out of which 62 events ranged in magnitude between 0.5 and 3.4. On an average, 5–6 events were recorded daily with a maximum of 18 tremors on 23 December 2003 and 2 January 2004. The low-magnitude swarm had moment release of the order of 6.7×10^{21} Nm. The swarm events showed a clustering in 2×8 sq. km area confined to two pockets of the urban area of Jind, apparently coincident with the NW–SE trend of the DSR[8].

Swarms are minor earthquakes occurring in a limited time and space with irregular variation and with no principal event. Different swarm activities during December 1993–October 2001 (total 11) in peninsular India were of short duration (varying from 20 days to 2–4 months), initiated during the monsoon to post monsoon (July to December) period[9]. The Jind swarm was also of the same nature.

Analysis of spatial distribution of seismic events (2001–04) indicates a pattern which conforms to structural attributes of the DFB. The subsurface strike-slip fault of the MDSSF provides a major discontinuity zone for nucleation of seismicity. Another clustering along the DSR reveals the presence of a belt parallel to the Himalayan fold system. This belt is of significance with regards to seismic hazard as it traverses across NCT Delhi. A total of 74 events with maximum magnitude of $M_L = 3.8$ (28 April 2001) was recorded within the political boundary of NCT Delhi.

The b value for the study period was computed using Gutenberg–Richter frequency magnitude relationship: $\log N = a - bM$, applying maximum likelihood solution (Figure 3 b), where N is the total number of earthquakes, M the magnitude, a and b are constants. The b value was found to be 0.79 ± 0.04, which is close to the normal value.

The fault plane solutions of earthquakes with $M_L \geq 3.0$ were ascertained based on first motion data (P-wave polarity), using the PMAN program[10]. Figure 4 shows the results for the event of 19 June 2002. The source parameters of all the 19 events are summarized in Table 2. The fault plane solutions show thrust with minor strike-slip (Figure 5). All the solutions have data consistency of the order of 90%. The focal planes of these 19 earthquake events either correspond to the DSR or MDSSF. Broadly, strike directions of 70% earthquakes conform to the trend of the DSR, whereas those of 20% events conform to the MDSSF. The nodal plane orientation for the rest of the earthquakes (10%) shows wide scatter.

For all the events, orientation of nodal plane 2 corresponds to either the DSR or MDSSF, except for three events. Earthquake events (1, 3, 4, 6, 9, 13 and 14) endemic to the MDSSF show a reverse fault mechanism on a steeply dipping plane (dip 64–85°) with oblique slip motion. The rake of the reverse/thrust slip ranges from 65° to 121°, with wide azimuthal variation. Earthquakes alluded to the NW–SE trending DSR fall in two categories: (i) the group of events (11, 16, 17 and 19) with reverse fault on a steep plane showing southerly dip; the rake values of slip ranging from 11° to 88°, and (ii) the group of events (2, 7, 8, 10, 12 and 18) with reverse fault on moderate to steep plane showing northeasterly dip; the rake values of slip ranging from 103° to 132°. The later group of events exhibits motion apparently mimicking focal mechanism of Himalayan Thrust domain[11].

Geoscientists and seismologists have been deeply concerned regarding the near ambience seismicity of Delhi. The tectonic model of the domain has already been reviewed[12–14]. The main tectonic elements of the DFB having been defined in unanimity are (i) MDSSF, (ii) GBF, (iii) Moradabad Fault, (iv) DSR, (v) Sohna Fault and (vi) Mathura Fault. The Sohna Fault is indicated by geomorphic

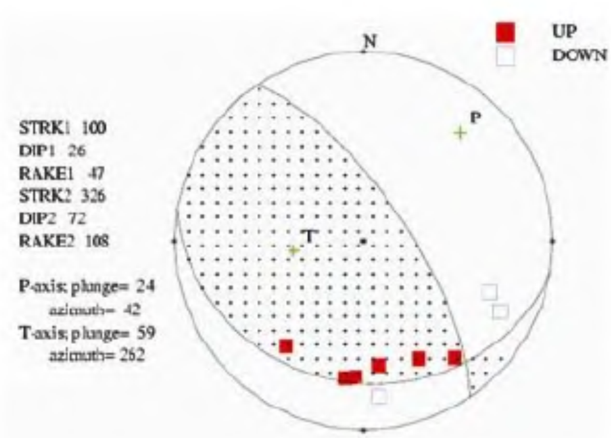

Figure 4. Fault plane solution of the event of 19 June 2002.

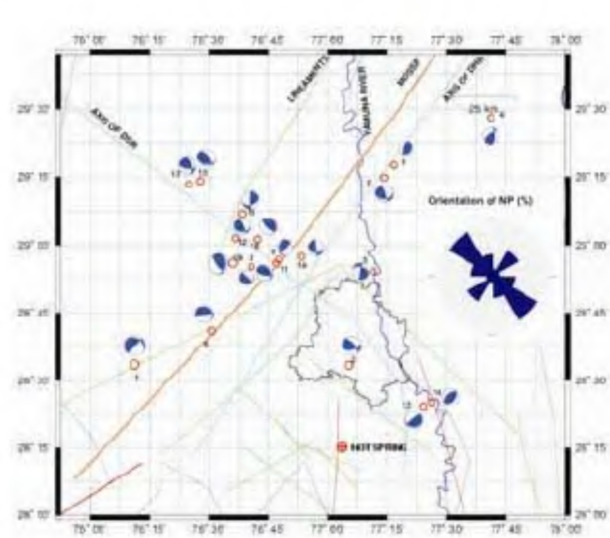

Figure 5. Fault plane solutions of events under the studied region. (Inset) Orientation of strike direction of plane 2 (% of 19 earthquakes).

Table 2. Source parameters of the events

Events	Date (yyyy mm dd)	Nodal plane 1			Nodal plane 2			*P* axis		*T* axis		
		S (°)	*D* (°)	*R* (°)	*S* (°)	*D* (°)	*R* (°)	*P* (°)	*A* (°)	*P* (°)	*A* (°)	*N*
1	2001 02 28	44	85	65	304	25	169	36	156	44	290	9
2	2001 04 28	76	48	37	318	63	131	9	20	53	278	8
3	2001 05 17	171	24	36	48	76	110	29	122	54	342	6
4	2001 07 07	1	40	44	234	64	121	13	302	59	189	6
5	2001 08 10	190	83	133	288	44	11	25	112	37	138	6
6	2001 09 12	323	14	154	79	84	78	38	180	50	336	8
7	2001 10 20	84	32	14	342	83	122	30	47	44	283	9
8	2002 05 10	66	13	23	313	85	102	39	32	49	237	7
9	2002 05 13	48	28	115	201	65	78	19	300	68	87	6
10	2002 06 19	100	26	47	326	72	108	24	42	59	262	10
11	2002 12 15	323	32	124	104	64	71	17	208	66	341	6
12	2003 04 02	87	26	22	337	81	114	31	7	49	273	6
13	2003 04 09	110	17	149	230	81	75	34	333	52	123	6
14	2003 06 16	35	37	79	228	54	98	8	312	79	171	6
15	2003 08 28	75	42	161	179	77	50	22	299	43	50	8
16	2003 09 13	323	17	96	136	73	88	28	228	62	44	6
17	2003 12 22	348	55	148	98	64	40	6	221	46	317	6
18	2004 03 17	355	82	124	97	35	14	29	58	43	297	7
19	2004 07 27	8	23	133	143	74	74	27	245	58	31	8

S, Strike; *D*, Dip; *R*, Rake; *P*, Plunge; *A*, Azimuth; *N*, No. of *P*-wave polarity.

and geothermal signatures, whereas Mathura Fault is grossly inferred to explain the Mathura earthquake event of 1 September 1803. As the domain has a cover of Quaternary sediments and rupture of earthquake incidences has not been observed, seismotectonic affiliation of these structural elements has not been unequivocally concluded.

The distribution of seismic events and their spatial patterns has been considered as clearly indicative of activities in this ambience of intraplate domain. Srivastava and Jalote[15] concluded that 'statistical analysis of instrumental data together with studies regarding stem rebound incremental and tectonic flux revealed that the NE–SW trending minima zone interpreted on the tectonic flux map possibly indicates a zone of fundamental feature in the basement having the pattern of regional tectonic lineaments, which is likely to have genetic relationship with the majority of earthquakes recorded in the region'. The 'minima zone' is coincidently the Delhi–Haridwar Ridge, now referred as the 'MDSSF'. It is needless to say that the inference above had been drawn based on scanty instrumental data.

Another effort of understanding earthquake behaviour of this domain has also been made[16]. The study was based on a network of stations at Rohtak, Sohna, Kasan and Delhi (ridge). The study concluded that, 'It is difficult to attribute the seismicity observed in Delhi to any particular fault or a lineament. It is possible that a number of lineaments are seismically active'. An important inference was that 'Rohtak (located NW of Delhi) is seismically most active and the northeasterly trend of seismicity along Delhi–Haridwar Ridge up to Main Boundary Fault (MBF) is supported in observation'. These findings were in agreement with the previous study done by Kamble and Chaudhary[7]. These studies were basically guided by limited dataset. After the establishment and operation of the Delhi Seismic Telemetry Network, new instrumental data have been generated which reflect significantly on the seismotectonics of the area. Attempts were made to understand the seismicity vis-à-vis results of Sonipat swarm observations[17] and focal mechanism of two events in the area[18].

The study of the new dataset of 288 events of various magnitudes ranging from 0.8 to 4.2 has brought about a pattern of clustering indicative of association with tectonic elements of the area. Two important inferences of the pattern analysis are: (i) the MDSSF, which was earlier referred to zone of minima 'tectonic flux', is area of the most significant zone. This amounts to clustering of 50% events with a narrow aperture zone (20 km) along the geophysically conformed trace of the fault, with a moment released of the order of 6.5×10^{22} Nm during the four year period from 2001 to 2004. (ii) Significance of the DSR – again a geophysically inferred zone of gravity high, in nucleating seismicity in the area.

The focal mechanism of earthquake events based on the constrained seismic monitoring network has been worked out for this area. The fault plane solutions further corroborate with the inference of pattern analysis highlighting preferred orientation of nodal planes along (i) the DSR and (ii) the MDSSF. The DSR, which was hitherto not considered in seismotectonic evaluation of Delhi and its ambience, has emerged as a feature of a consequence as regards to earthquake hazard of Delhi. Shukla *et al.*[18]

presented focal mechanism solutions of two events (events 1 and 2) using FOCMEC under the SEISAN analysis software[6], which is in agreement with the result of the present study using PMAN[10] analysis program. The present study of focal mechanism of 19 events reveals the compressional tectonics in the ambience, where the dominant fault mechanism in nucleating seismicity is thrust with minor strike-slip. The strike direction of fault planes for majority of the events conforms with the orientation of the DSR, trending NW–SE with dips ranging from 60° to 86°. The focal mechanisms noted along the DSR are strikingly similar to those for earthquake events in frontal fold domain and MCT in the Himalayas[11]. Hence the DSR with its NW–SE trend mimics the compressional seismotectonic behaviour of the thrust domain of the Himalayas. This, in other words, reflects that earthquakes in this part of the peninsular domain are the result of back thrust of continent–continent collision.

The strike-slip fault MDSSF transcends into Himalayan Frontal Thrust Fold Belt (HFT), probably works as guide plane in transmitting the back thrust in the Delhi ambience. The MDSSF trends NNE–SSW oblique to the HFT (the region of convergence of Indian and Eurasian plates) lying in ideal condition of reactivation of near parallel planimetric disposition vis-à-vis plate motion. The MDSSF, geologically inferred strike-slip fault[12], is now, found to get reactivated as 'thrust' with minor strike-slip component, in the imparted tectonic domain of back thrust.

The seismicity pattern analysis suggests mainly two zones of significance, namely MDSSF trending NNE–SSW and DSR, trending NW–SE. The fault plane solutions of analysed events further corroborate with the inference of pattern analysis highlighting preferred orientation of nodal planes either along the DSR or MDSSF.

The DSR with its NW–SE trend mimics the compressional seismotectonic behaviour of the thrust domain of the Himalayas. The MDSSF, is found to get reactivated as 'thrust' with minor strike-slip component. The concept of reactivation of MDSSF and DSR, in the impending back thrust domain sets a new task of realistic assessment of seismic hazard through near field seismicity in Delhi ambiance.

The existing seismic monitoring network is of large aperture and the region has thick alluvial deposits. The present study of focal mechanism solutions and analysis is based on limited and the best available dataset so far. This could be better addressed with further improvised systems of seismic monitoring. In this context it would be worthwhile to increase the density of the seismic network, deploying additional broadband systems in proximal array around Delhi.

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