



Seismicity around the Mahendragarh–Dehradun basement fault in the western Ganga plain, India: a neotectonic perspective

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Abstract

The NE–SW trending Mahendragarh–Dehradun Fault (MDF) is a basement fault in the western Ganga plain. The earthquake ($4.7 m_b$) epicentered on this fault on 2nd June 2017 was focused around 10 km depth and does not show any surface rupture. Ground Penetrating Radar (GPR) survey around the epicenter detects few shallow-depth subsurface normal faults parallel to the MDF. However, it is unclear whether these normal faults are linked with the 2017 earthquake or other previous earthquakes. Seismic record (USGS) since 1975 to 2017 suggests occurrence of 22 earthquakes ($\sim 5 m_b$) around the MDF and majority ($\sim 63\%$) of these are clustered around Delhi and Rohtak. Following the 2017 earthquake, frequency of earthquakes occurrence sharply increased than previously recorded instrumentation period from 1975 to 1995. Majority of the seismicity is focused around 10 km depths, shallowing to depths of 25–207 km recorded from 1975 to 2004. Earthquakes clustered along the Main Himalayan Thrust (MHT) shows similar temporal trend as near the MDF. Southward thrust movement of the Himalaya orogenic wedge predicts to impose strike-slip motion on the orthogonal-oriented steep basement faults, which is consistent with geologic and geomorphic field relations, and seismicity focal mechanisms along the MDF. The observed upper crustal deformation associated with such fault deformation pattern may be partly influenced by the MDF and partly by the foreland bulge seismicity. Potential tectono-geomorphic parameters and soil-chronosequence may suggest the surface deformation is active through the Holocene.

Keywords Himalaya · Basement fault · Ganga plain · Earthquakes · Neotectonics

Introduction

Precambrian basement of the Indian peninsula is flexed and buried under thick pile of Tertiary-Quaternary sediments of the Ganga plain. Southern margin of the Ganga plain is confined by the peripheral bulge produced by increased loading in the Himalayan orogen caused down-bending of the under-thrusted lithospheric plate (Agrawal et al. 2002) in Late Quaternary (Singh and Bajpai 1989). Though the location, wavelength, and amplitude of this flexural bulge are not readily apparent as the Indian shield surface is deeply

eroded (Bilham et al. 2003). The peripheral bulge is characterized by long-wavelength elevation in a magnitude of few hundred meters (Singh and Bajpai 1989; Singh 1996). It is coinciding with the NW–SE trending Delhi-Sargodha High (Blisniuk et al. 1998). Geological and geophysical evidences (Sastri et al. 1971; Valdiya 1976; Kumar et al. 2013; Godin and Harris 2014) suggest the basement is cut by fault-bounded ridges and troughs underlying the sediments cover (Rao 1973; Raiverman et al. 1983; Kumar et al. 2013) and hence sediment thickness in the plain varies laterally and longitudinally from up to a few meters to a several kilometers both along the ridges or in the depressions. Intraplate seismicity in this region is likely due to the strain produced in the Indian lithosphere, imposed by northward convergence of the Indian plate being accreted with Eurasia (Dubey et al. 2012). The basement faults bordering the ridges in the Ganga plain may represent old basement faults formed prior to India-Asia collision (Gahalaut and Kundu 2012; Godin and Harris 2014). Favorably oriented orthogonal-faults to the Himalayan orogen could promote

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reactivation as normal or strike-slip faults. Their interaction with the Himalayan front causes seismicity in the Ganga plain (Raval 2000; Thakur 2004; Arora et al. 2012; Kumar et al. 2013; Verma et al. 2017). These faults experience both normal and strike-slip motions as evidenced by previously studied focal mechanism solution of the earthquakes associated with the MDF (Shukla et al. 2007; Prakash and Shrivastava 2012). Southwestwardly deviation of stress field contours along these basement faults suggests that, along the MDF and other basement faults; the stress field migrates into the Indian peninsular region (Fig. 1). Frequent earthquakes of varying focal-depths from 10 to 207 km (USGS 2017) have been observed near the vicinity of this fault, which include both strike-slip and normal fault focal mechanism. Focal depth and magnitude of these earthquakes control the degree of surface rupture.

Occurrence of numerous shallow-focus earthquakes (less than 70 km, Ram and Yadav 1982; USGS 2019) along the MDF is a clear manifestation of active nature of this fault (Fig. 2). Our ability to infer the tectonic regime using earthquake data is conducted via an integrated study using GPR and tectonic geomorphological analysis. As the fault projects to extend near the vicinity of Delhi, the national capital and a densely populated area (> 2.4 million population, Fig. 3), a substantial knowledge about the behavior of the fault is necessary for the hazard risk assessment of the region. Other prominent tectonic features in and around Delhi region are: Delhi-Haridwar ridge (DHR), Sohna fault and Moradabad fault (Fig. 2; Bansal and Verma 2012; Prakash and Shrivastava 2012). This region lies in the seismic zone IV (IS 1893-Part 1, 2002) and is classified as tectonically active region (Das et al. 2018). An earthquake of magnitude 4.7 m_b occurred at 10 km depth, epicentered at Rohtak, Haryana on 2nd June 2017. Due to thin cover sediment (~40 m around

Rohtak), surface ruptures was expected. However, fieldwork around the epicenter region revealed no surface rupture or any other kind of damage to the property. 2-D Ground Penetrating Radar (GPR) survey around the epicenter region documents evidence of many subsurface normal faults at shallow-depth. However, their strike-slip component if any cannot be detected from the 2-D GPR profiles. In addition, it is unclear whether these normal faults are associated with the 2017 earthquake or any other previous earthquakes. In this study, we evaluate seismic data from various depths around the MDF in correlation with tectono-geomorphic and soil-chronosequence analyses.

Analysis of recently recorded epicenters around this fault reveals the occurrence of a series of earthquakes in recent years with varying magnitude (3.7 m_b to 5.1 m_b) and focal-depth (10 to ~207 km). ~63% of earthquakes are clustering around the national capital Delhi and Rohtak, on the flexural bulge of the basement. Earthquake occurrence was low between 1975–1995 (3 events), and then increased in frequency from 1995 to 2017 (19 events). Majority (~63%) of earthquakes are focused around 10 km depth. Geomorphic markers such as offset streams, linear streams patterns, and topographic profile across the fault may suggest the MDF connects with these shallow subsurface faults as a seismically active fault system. The associated soil chronosequence (Bhosle et al. 2008; Pati et al. 2018) suggests that major activity along this fault occurred since at least 4.5 Ka during which major relief changes occurred across the fault. The present and paleo-fluvial geomorphology across the fault are validating with the historical and recent seismic data.

Geological setting

Basement configuration and the basement faults in the Ganga plain have been mapped using aeromagnetic survey (Agocs 1957), drilling and geophysical survey (gravity, aeromagnetic and ground magnetic, reflection and refraction seismic survey) by Oil and Natural Gas Corporation (ONGC) (Sastri et al. 1971; Rao 1973; Karunakaran and Ranga Rao 1976; Raiverman et al. 1983). Based on the aeromagnetic and gravity survey, basement faults have been mapped by the geological survey of India and published in the seismotectonic atlas of India (GSI 2000). From the seismotectonic atlas of India, we have traced the MDF which runs NE–SW about 295 km, along with the eastern margin of the Delhi-Haridwar subsurface basement ridge (Fig. 4). This westernmost basement fault in the Ganga plain links the Himalayan Frontal Thrust (HFT) in the north to the Indian peninsular craton in the south, cutting through the peripheral flexural bulge of the Indian peninsula. This fault meets the HFT where the

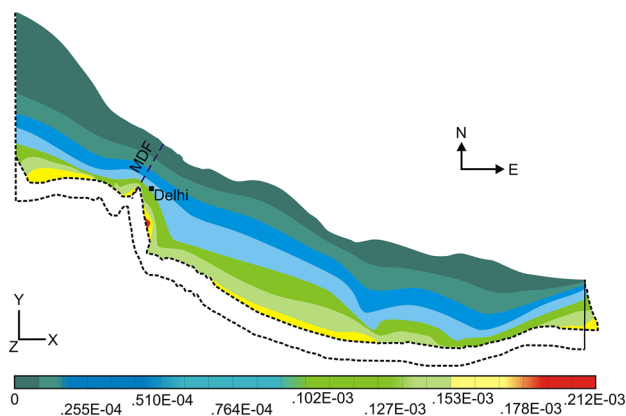
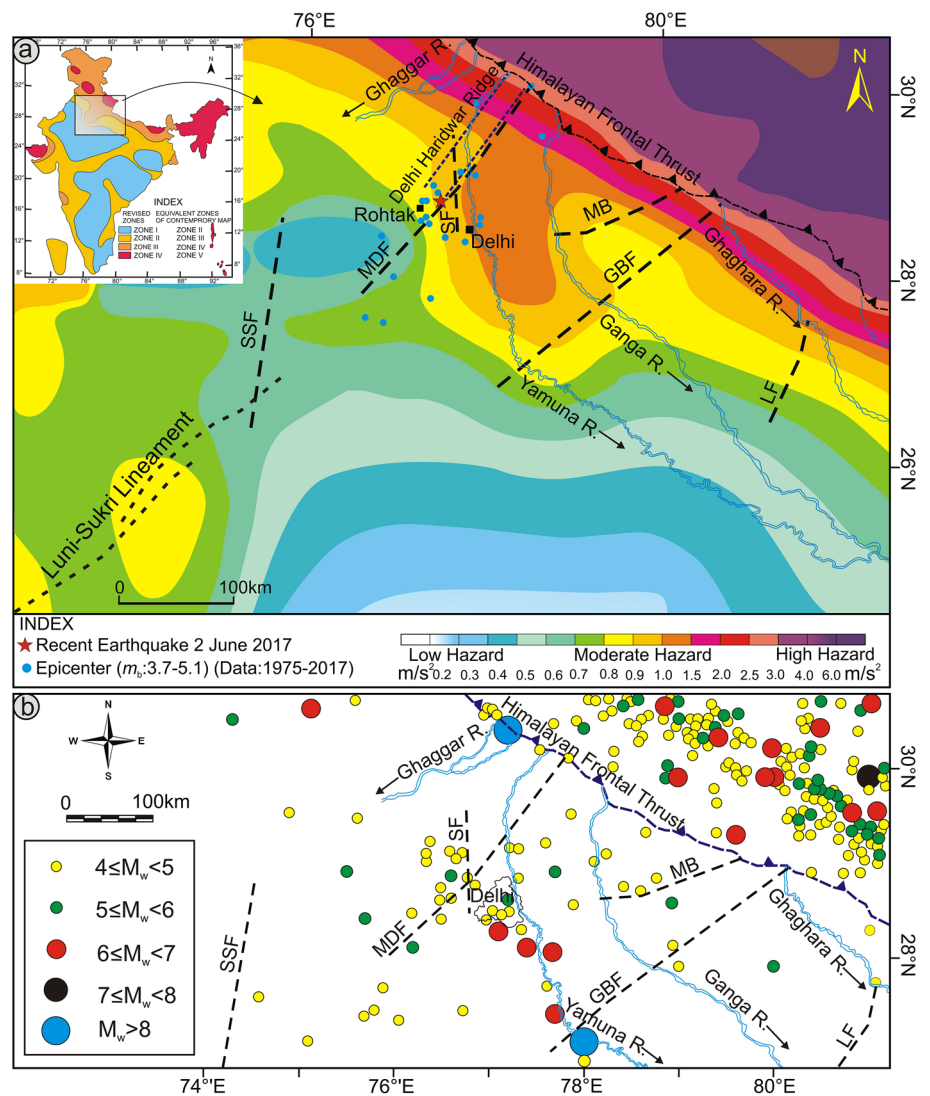


Fig. 1 Stress field in the Ganga plain based on distribution and orientation of faults. Locations of basement faults show deviation of stress contour indicating stress transfer towards the peninsular region (after Das 2008)

Fig. 2 **a** Seismic hazard map of the study area (data compiled from <https://asc-india.org>), inset shows seismic zone of India with location of study area and **b** Seismicity and fault map of western Ganga plain. Sardarsahar Fault (SSF), Mahendragarh-Dehradun Fault (MDF), Sohna Fault (SF), Moradabad Fault (MF), Great Boundary Fault (GBF), Lucknow Fault (LF) (seismic data taken from Prabhu and Raghukanth 2015)



outer Himalaya shows local strike deviation (the Siwalik hills show local change in orientation from N58°W in the western side of the fault to S17°E in the eastern side of the fault; Supplementary Fig. 1). Several authors (Bilham et al. 1997; Powers et al. 1998; Lavé and Avouac 2000; Jade 2004; Burgess et al. 2012; Gavillot 2014; Gavillot et al. 2016) have calculated varying rates of convergence at the thrust front in different parts of the Himalaya. Geotectonically-constrained convergence rate between India and Tibet at the junction of the MDF with the HFT is estimated to be 10–18 mm/year (Jade 2004). The cover sediment (mainly alluvium) thickness over this fault varies from 3000 m around the HFT (close to the Himalayan mountain front) to about 40 m around Rohtak (epicenter of the present earthquake, GSI 2000). Due to this tectonic setting, this fault coinciding with the fore-bulge experiences frequent seismic events.

Methodology

Methodology in this study includes tectonic geomorphology, seismic record (1975–2017), and GPR data across the fault.

Tectonic geomorphology

In the Ganga plain, tectono-geomorphological features has been successfully used to map active surface faults (Singh et al. 2006; Bhosle et al. 2008; Pati et al. 2011a, 2019). In this study, role of active tectonics in characterization of the fluvial landscape around the MDF (fault zones) has been investigated through digital topography (SRTM-30 m) and morphometric analysis.

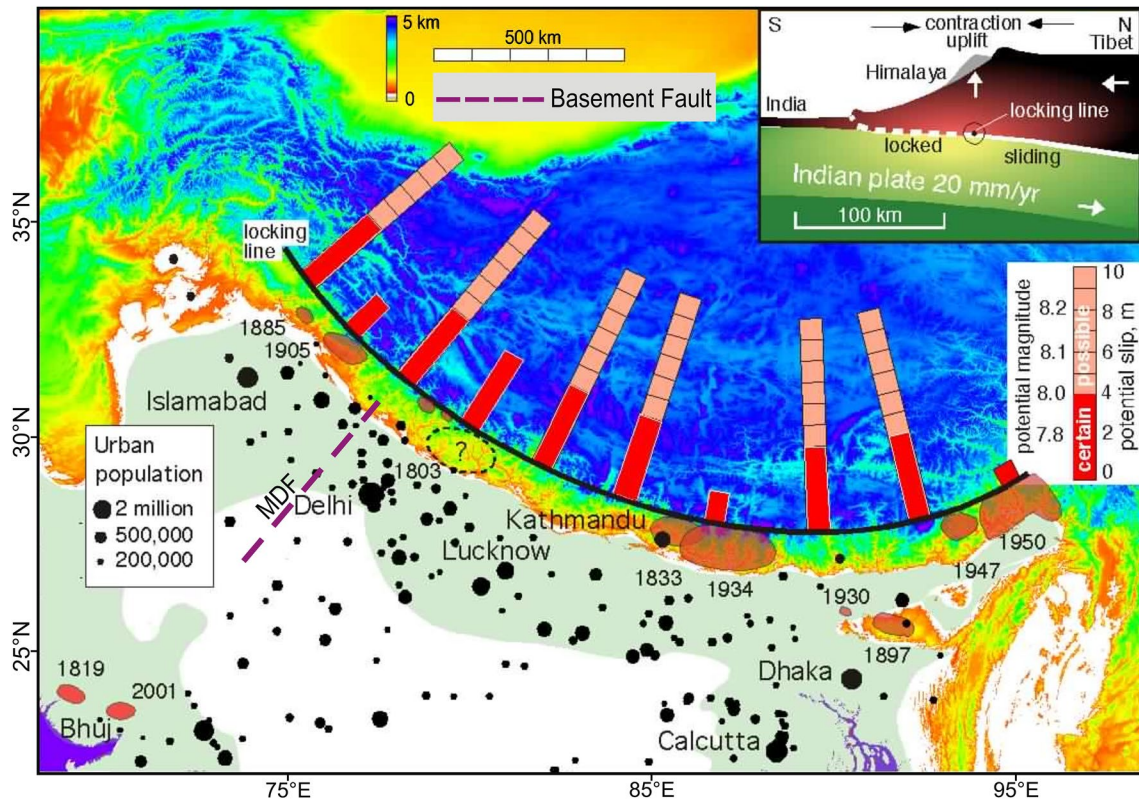
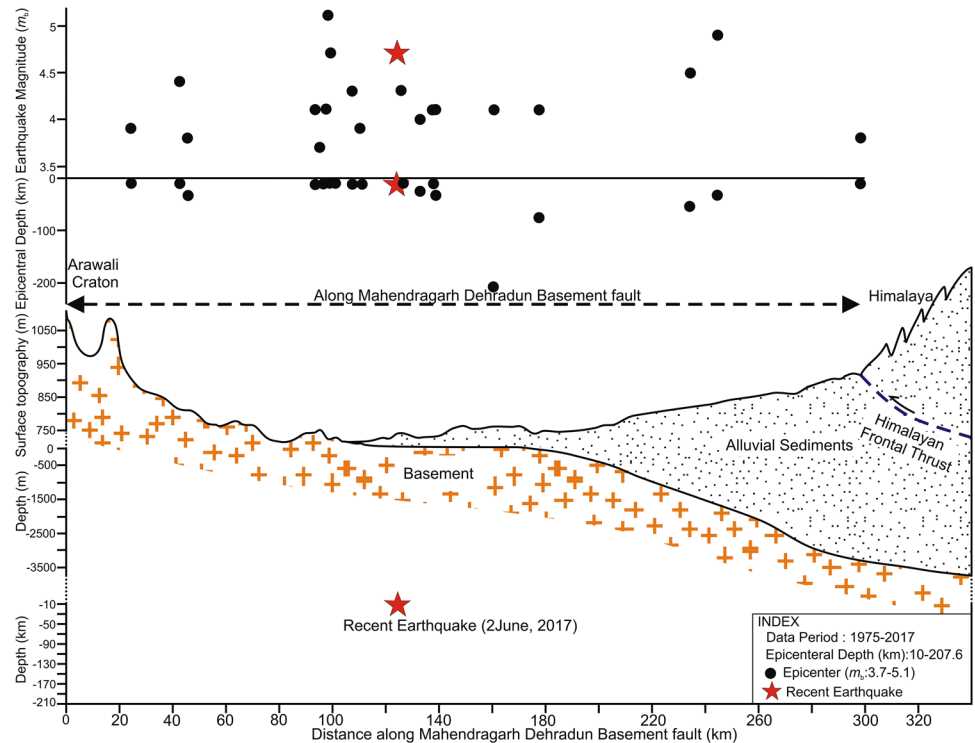


Fig. 3 Indo-Asian collision zone shows the estimated slip potential along the Himalaya. Shaded areas with dates are the epicenter and zones of rupture of major earthquakes in the Himalaya and the Kachchh region. (Inset) This simplified cross section through the Himalaya indicates the transition between the locked, shallow por-

tions of the fault that rupture in great earthquakes and the deeper zone where India slides beneath southern Tibet without earthquakes. Between them, vertical movement, horizontal contraction, and seismicity are currently concentrated (modified after Bilham et al. 2001)

Fig. 4 The plot shows the correlation between the earthquake magnitude and focal-depth falling in the fault zone of the MDF throughout its length. Cross-section represents the basement and surface profile along the same length of the fault



Morphometric analysis

Surface movements produced by active faults affect the topography as well as the drainage response (Jackson and Leeder 1994). Morphometric analysis is being used as a powerful tool to quantify uplift, incision and erosion rates, and slip rates on faults at short (103–106 year) time scales (Burbank and Anderson 2001; Keller and Pinter 2002). Previous studies in the Ganga plain have used alluvial channels to interpret for local tectonic control to surface responses (Singh et al. 2006; Bhosle et al. 2009; Pati et al. 2011a).

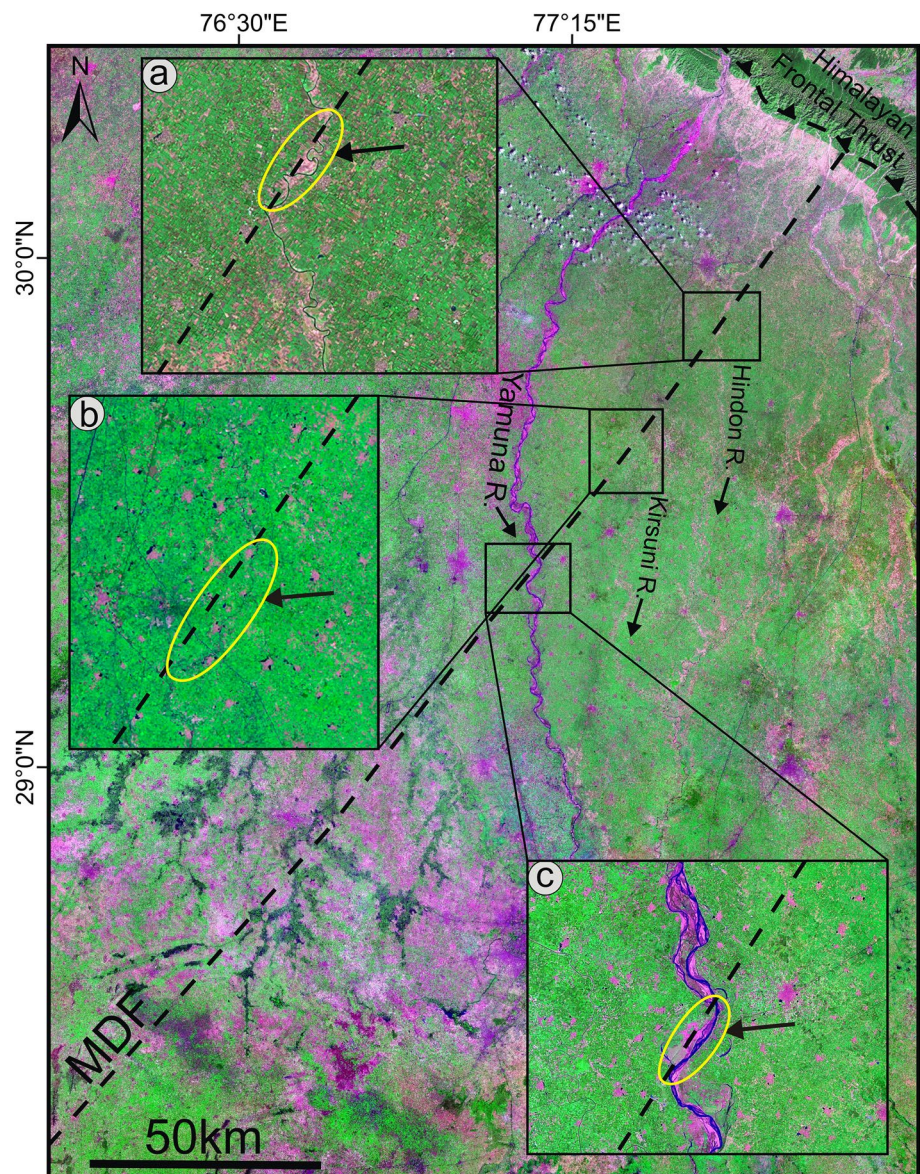
Commonly used morphotectonic indices such as basin asymmetry, longitudinal and transverse channel profiles, Sinuosity Index (SI), valley width/height ratio and abandonment of paleo-courses of channels are generally used to evaluate the relationship between tectonics and geomorphic

response (Bull and McFadden 1977; Bull and Wallace 1985; Pinter and Wallace 1996; Raj et al. 2003; Silva et al. 2003; Goudie 2004; Jacques et al. 2014; Kale et al. 2014). In this study, we integrate morphotectonic parameters, SRTM DEM (30 m) analysis, published topographic maps and ETM+ imagery from LANDSAT-7. Distance around 30 km across the MDF zone was studied for morphotectonic parameters. Drainage morphometry of rivers such as Yamuna, Kirsuni and Hindon which are passing through the MDF zone were analyzed. Satellite imagery (ETM+, Band combination of 7-4-2, Fig. 5) has been used for the drainage anomaly study.

Tectonics and associated channel morphology

Drainage analysis is a powerful tool to infer recent tectonic activity and uplift (Ouchi 1985; Clark et al. 2004; Delcaillau

Fig. 5 Offset drainage identified in the study area. Standard FCC (ETM+ image, 7-4-2 band combination). The satellite image shows offset channel of Hindon, Kirsuni and Yamuna rivers across the fault in enlarged view of rectangles a, b, c, respectively



et al. 2011), as river channels are very sensitive to changes in the parameters that control their shape and gradient (Whipple and Tucker 1999). Stream development and channel response can serve as sensitive morphometric indicators to reinforce evidence of active deformation, including faults evolution in an area. Drainage patterns in an area of active deformation reveal aspects of faults and anticline growth (Medwedeff 1992; Mueller and Talling 1997; Delcaillau et al. 1998, 2006; Burbank and Anderson 2000; Husson and Mugnier 2003; Gupta and Ellis 2004; Sung and Chen 2004). Climate and lithology play equal roles in drainage morphology and reorganization. Channel reorganization and evolution can provide insights of potential tectonic control. Structural control on a river system can be inferred from various observations such as abrupt changes in river morphology from braiding to entrenched meanders, alluvial fills accumulation, flow direction, offset or linear channels, location of sag-ponds or springs, convexity and knickpoint in longitudinal river profiles (Holbrook and Schumm 1999; Schumm et al. 2002; Singh et al. 2006; Miller et al. 2012; Whittaker 2012). We have identified several of these characteristics near the inferred location of the MDF fault zone along the Ganga plain (Fig. 6), which have been investigated and discussed.

Parallel drainage patterns are usually found where there is pronounced slope or bedrock structural control, which lead to regular spacing of parallel or near-parallel streams (Thornbury 1989). This has been observed in the northern part of the study area (piedmont zone) where due to steep slope streams show parallel to sub-parallel pattern. Segments of the Yamuna river and its tributaries are oriented parallel to the MDF which may indicate the effect of fault on channel orientation (Fig. 6).

Offset of stream channels Large-scale river channel deflections may infer strike-slip fault offsets (Bloom 2002; Zámolyi

et al. 2010). However, normal faulting can equally produce offset channels, if motion of the uplifted or tilted block is oblique to the regional slope, where the stream course deviates to follow the fault for a few kilometers, crosses the fault at a lower elevation and continues along the regional slope (Singh et al. 2006; Supplementary Fig. 2). Across the MDF, the Yamuna, Kirsuni and Hindon rivers offset of 5, 7.5, and 3.5 km, respectively, may suggest structural control on the local drainage patterns that coincide with the inferred locations of the MDF (Fig. 5). Some of the largest river meanders in the Yamuna, Kirsuni, and Hindon rivers that have apparent deflection to the southwest (versus to the S or SE) coincides with the inferred surface projection of the MDF.

Initiation of new streams along the fault zone New streams generation in the fault zone of normal and reverse faults is common in the Ganga plain (Singh et al. 2006; Bhosle et al. 2009; Pati et al. 2011b). Initiation of several such new streams near the Yamuna, Kirsuni and Hindon rivers align linearly along the MDF (Fig. 6). We interpret here that these first-order stream originates in response to gully erosion and vertical relief across the fault zone.

Longitudinal profile of rivers and knickpoints Longitudinal river profile is a very sensitive linear aspect of tectonic deformation in the earth crust (Demoulin 1998; Holbrook and Schumm 1999; Whittaker et al. 2007; Lahiri and Sinha 2012; Viveen et al. 2012; Fekete and Vojtko 2013; Goren et al. 2014) and hence is a universally practiced tool in tectonic research (Roy and Sahu 2015). Long profiles of alluvial channels and many bedrock or mixed-bedrock-alluvial channels are typically concave-up, a shape traditionally equated with a graded, equilibrium profile (Mackin 1948; Pazzaglia et al. 1998; Whipple 2004). Deviations from this may indicate that the fluvial system is in a transient state of adjustment to a base level, tectonic, climatic, or rock-type

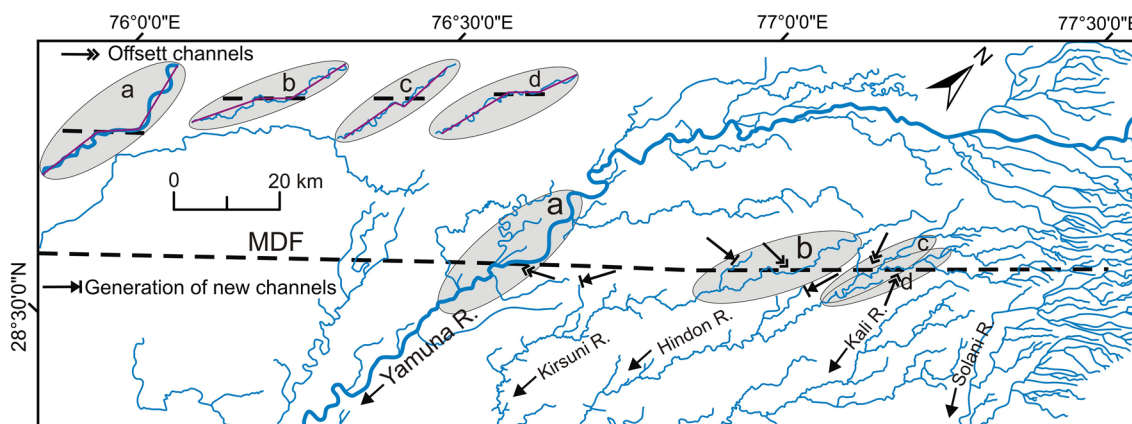


Fig. 6 Geomorphic signatures of modern channels around the MDF

perturbation (Molin and Fubelli 2005). In particular, convex segments called knickpoints or knickzones depending upon their length can be investigated to evaluate their coincidence with tectonic perturbations at scales ranging from the whole chain to local structures (Molin and Fubelli 2005). Knick-points in a longitudinal river profile could serve as good indicators of active structures (Wobus et al. 2005; Delcaillau et al. 2011) along the path of a river. Fault movements can generate many small knickpoints within a channel profile (Zhang et al. 2011). In this study, longitudinal river profile has been prepared for the Yamuna, Kirsuni and Hindon rivers (Fig. 7) using SRTM DEM. All three rivers show multiple local convexities along the longitudinal river profiles. Some of these local river convexities associated with knick-points coincide with the intersections of the MDF along the Yamuna and Kirsuni rivers (Fig. 7). Hence we interpret here that some of these knickpoints are related to fault activity. It is important to note that several knickpoints do not align with known evidence of faults, which may relate to transient drainage integration from river confluences and/or

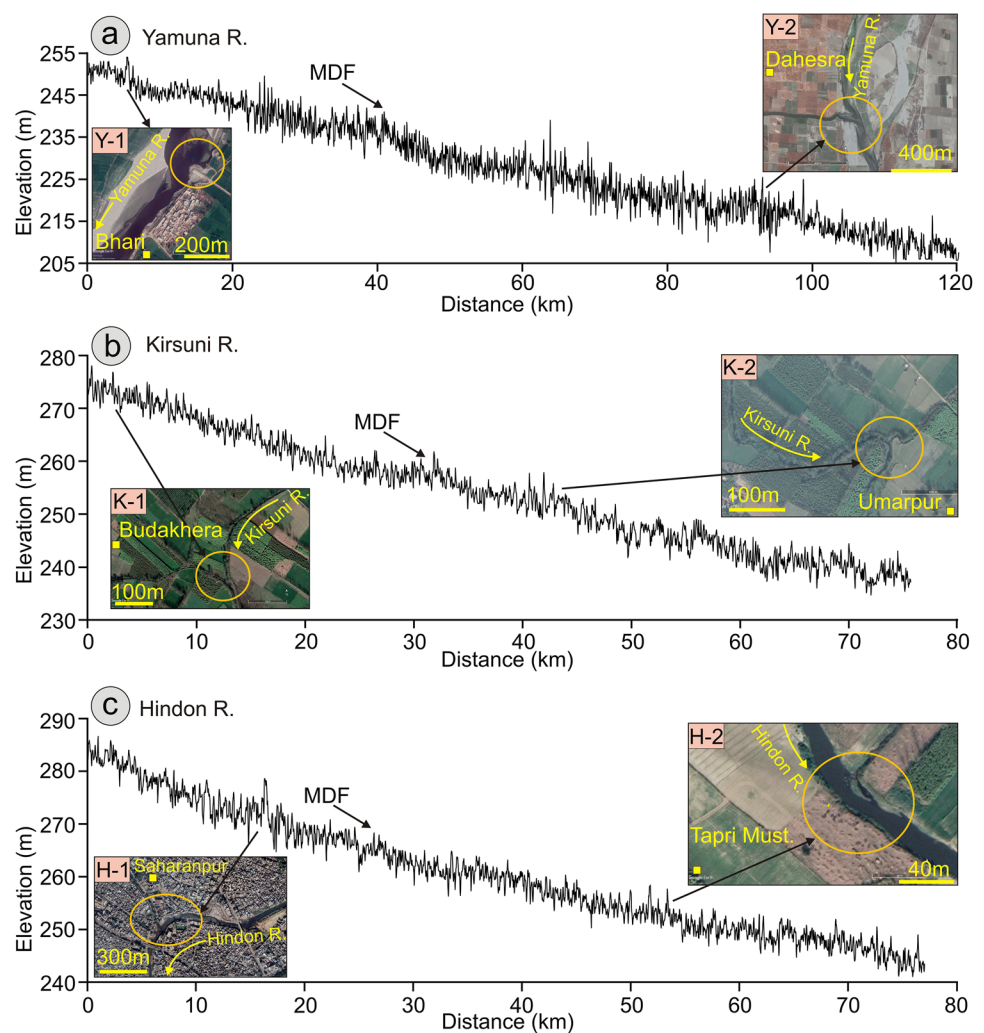
anthropogenic activities (Fig. 7). The Hindon river shows no prominent local convexity across the location of the MDF (Fig. 7), and may be attributed to a deeper fault location and more diffuse surface response of the MDF buried beneath thick (~2500 m) local sediments cover (GSI 2000).

River style River style is one of the tools which define the tectonic activity along the river course. The Yamuna river shows significant change in channel style while crossing the MDF, from braided channels (upstream of the fault) to anastomosing channels (downstream of the fault). In fact, this river shows anastomosing channels pattern up to a distance of about 5 km (Fig. 8). This can be explained in terms of slope change across the MDF and locally increased sediment production by river bed scouring.

Paleochannels around the MDF

Ancient civilizations were built-up along the river banks in India (Valdiya 2002). Traces of paleochannels mapped

Fig. 7 Longitudinal river profile of the rivers **a** Yamuna, **b** Kirsuni and **c** Hindon. (Y-1, Y-2) shows anomaly due to confluence of the streams with the Yamuna river and anthropogenic activity. (K-1, K-2) shows anomaly due to confluence of the stream with Kirsuni river. (H-1, H-2) shows anomaly due to confluence of the stream with Hindon river and anthropogenic activity



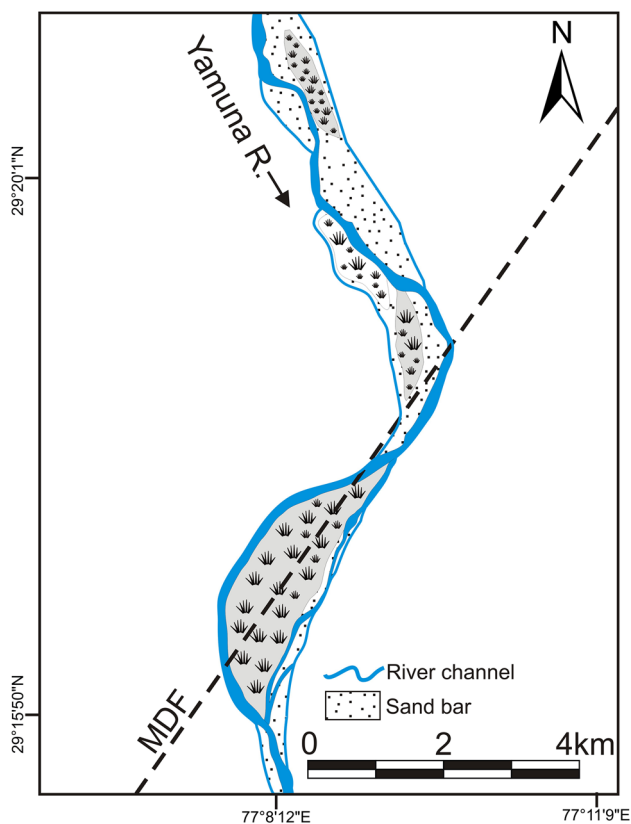


Fig. 8 Yamuna river around the MDF. The upstream block shows numerous braid bars whereas, the downstream block shows anastomosing channel properties

by integrating locations of ancient civilization sites in this study show abrupt end along the MDF (Fig. 9). Abrupt ending of multiple paleochannels along a tectonically adverse feature (MDF in this study) may be interpreted as tectonically caused rather than climatic. A recent compilation of the ancient civilization sites by Uesugi (2018) suggests the paleochannels in the area were parts of the paleo-Ghagghar-Hakra and Paleo-Yamuna river systems. Optically stimulated luminescence (OSL) chronology of these paleochannels was carried out in the OSL laboratory in the Department of Earth Sciences, Indian Institute of Technology, Roorkee, India. The data yields the abandonment of these coeval channel systems occurred between 2.5 and 3 Ka (Pati et al. 2018) which is inferred due to fault-related uplift from the MDF and other associated surface faults.

Soil-chronology and soil properties around the MDF

Soil-chronology and soil properties have been used in the Ganga plain to demarcate active faults (Singh et al. 2006; Bhosle et al. 2008; Pati et al. 2018). In this study, soil properties such as solum thickness, degree of pedality, and B-horizon thickness have been used to distinguish the

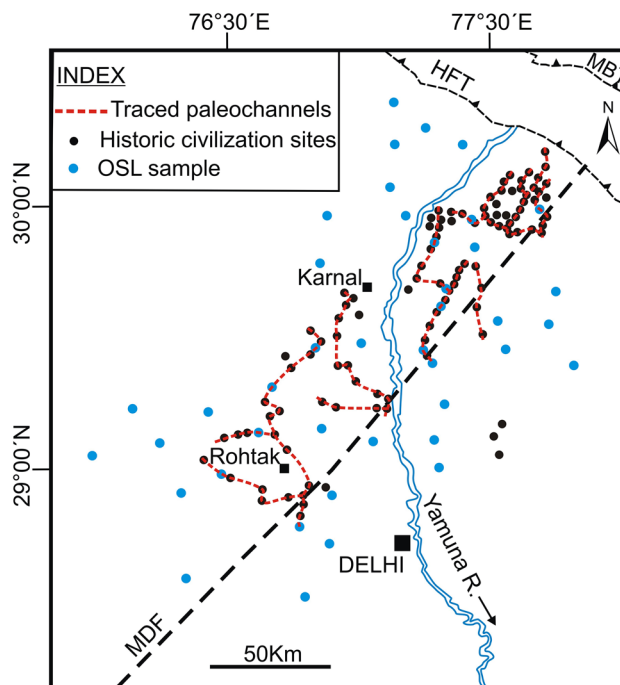


Fig. 9 Paleochannels mapped by integrating historical civilization sites shows abrupt ending along the MDF and OSL sample locations are marked around the MDF (Data source: Valdiya 2002; Bhosle et al. 2008; Pati et al. 2018)

fault zone-soil from either side of the fault (Table 1). Solum thickness on the NW and SE block of the MDF varies up to 450 cm and 320 cm, respectively, with well developed pedo-features. However, the fault zone shows weakly developed soil with solum thickness varies up to 150 cm. This contrasting soil properties may be explained as lower degree of soil development from a younger sedimentation event localized in a linear trough mapped along the MDF (Fig. 10).

GPR study around the MDF

The recent 2nd June 2017 earthquake was studied by field work and shallow subsurface sediment offset using GPR around the epicenter. During fieldwork conducted between 4th June to 8th June 2017 around Rohtak and nearby area within 20 km radius of the epicenter (Fig. 11), no surface rupture (geomorphic or infrastructural) were found.

GPR instrumentation consisted of a shielded antenna of 100 MHz (GSSI-SIR-3000) was used for this investigation. The antenna of this range provides the best balance between depth of penetration and resolution (Bristow and Jol 2003; Neal 2004). GPR profiles were taken in distance mode (using survey wheel) along straight lines transverse to the strike of the MDF. Fiber optic cable was used for data transfer from the antenna to control unit. All sources of electromagnetic waves such as mobile phones, hyper-tension

Table 1 Detailed description of various pedons across the Mahendragarh–Dehradun Fault (Refer Fig. 10 for location)

Location of soil profile	Solum thickness (cm)	B horizon			Mottles/Fe–Mn concretions in horizon	
		Thickness (cm)	Structure	Color		
Kakrana	450	300	Well developed sub-angular blocky structure	2.5 Y/2 5/4, 6/4	Sandy Loam	Fe, Mn nodules in A and B horizon
Gangtan	150	100	Weakly developed pedo-features	2.5 Y 5/3	Sandy	Mottles in BC horizon
Bhaproda	320	200	Well developed sub-angular blocky structure	5 Y 5/2 5/4, 6/4	Sandy Loam	Fe, Mn nodules in B and C horizon

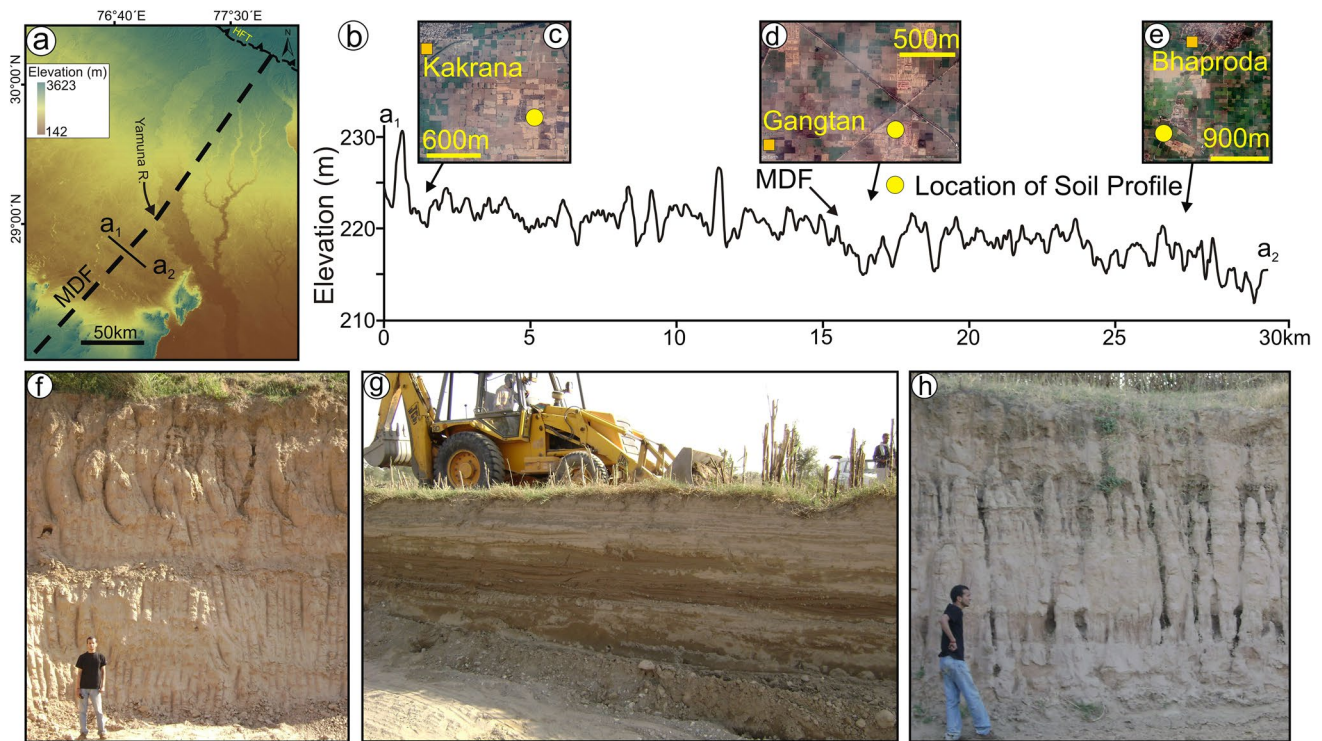


Fig. 10 **a** SRTM DEM of the study area, a_1 and a_2 mark the location of topographic profile and soil profile across the MDF, **b** topographic profile along the a_1 and a_2 , **c–e** are field locations of soil profile in

upthrown block, fault zone and downthrown block, respectively. Studied soil profiles at **f** Kakrana, **g** Gangtan and **h** Bhaproda

lines and electric poles were avoided to the best possibility to avoid any signal interference while working the equipment. Running vehicles, passing trains or other heavy traffic which cause vibrations and induce noise in the data were also obviated. The GPR was moved on a plain surface with no grits or gravels to avoid noise to the data. Each GPR profile was about > 1 km length. The range of the signal for depth penetration was kept at 800–1000 ns.

The collected data were processed with RADAN-5 software as methods suggested by Fisher et al. (2000) and GPR manual provided by Geophysical Survey System Instruments (GSSI). Data processing software and tools were used through the Finite Impulse Response (FIR), Infinite Impulse Response (IIR), gain control, 2-D spatial fast

Fourier transform filters, deconvolution, surface normalization, hyperbola migration, and band pass filtering. For the data processing obtained from GPR at 100 MHz frequency, the filter bandwidth applied was 40/50 and 150/180 MHz as suggested by Fisher et al. (2000). Reflection of the waves caused by the air and other surficial matters were removed.

GPR profiling around the area (Fig. 11) reveals the presence of many near-vertical faults with apparent normal fault offset (Fig. 12) at the basement sediment interface. No clear evidence of strike-slip offset can be resolved from the GPR profile. Around Rohtak (Fig. 11), multiple vertical faults are observed to a depth of ~40 m with a throw of ~5 m (Fig. 12). These apparent normal faults could have been linked with the recent earthquake or any other previous earthquakes.

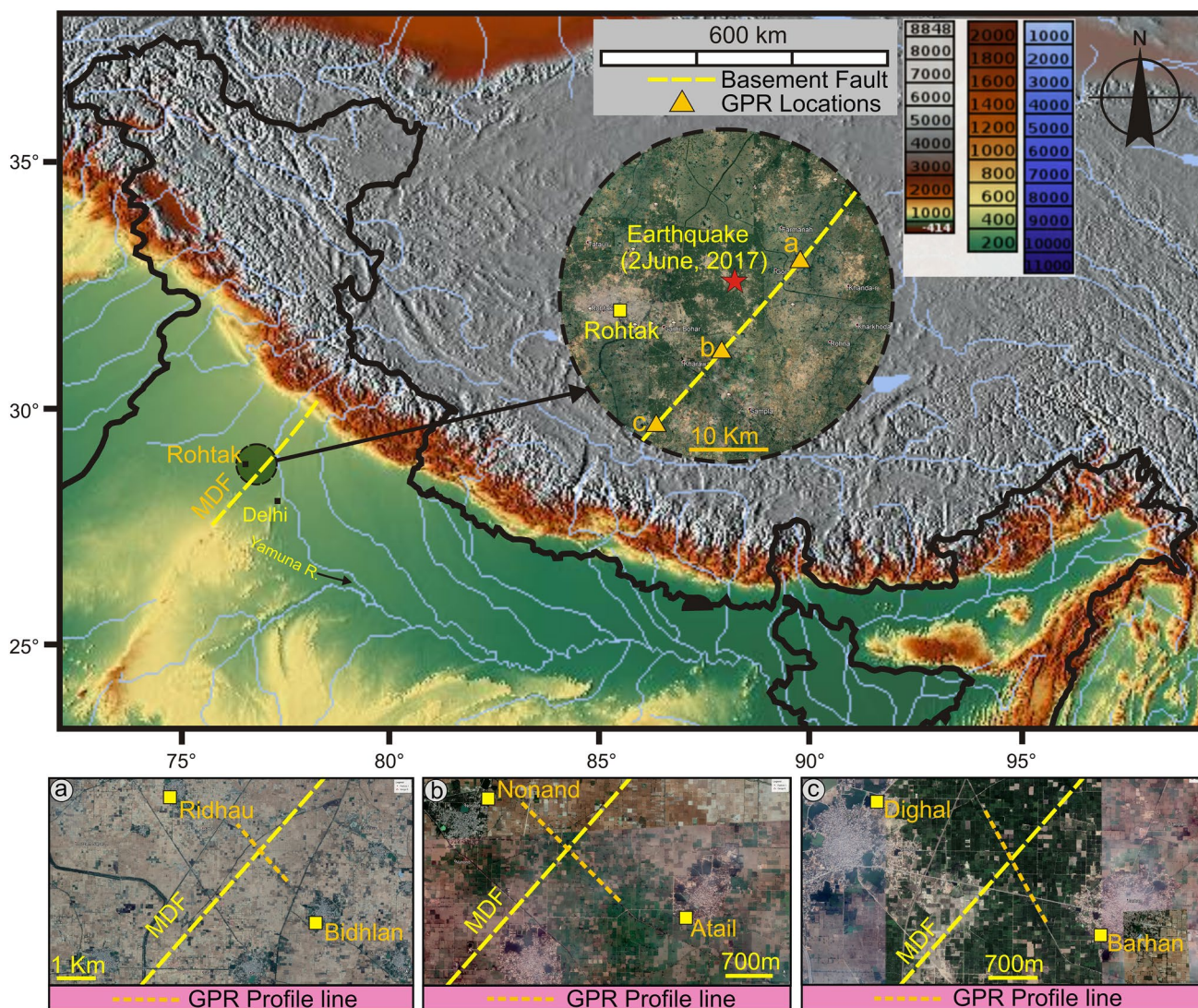


Fig. 11 Location of GPR profile across the MDF, enlarge view of circle shows study area around the epicenter of recent earthquake on 2nd June 2017 with GPR profile locations, a–c shows detailed locations of GPR profile on Google earth image

These shallow faults may or may not connect at depth to the deeper inferred MDF fault resolved presumably by geophysical investigations such as aeromagnetic, ground magnetic, gravity and seismic surveys and the deep drilling conducted in the area (Sen-Gupta 1964; Fuloria 1969; Sastri et al. 1971; Valdiya 1976). Nature of these steep vertical faults suggests that the MDF is more likely controlled at the shallow subsurface as normal fault system.

Study of recent earthquakes around the MDF

Recent earthquake data and trend of seismicity was studied using USGS earthquake catalog (1975–2017). Distribution of twenty-two earthquakes ($3.7 m_b$ – $5.1 m_b$) occurred around the MDF since 1975 to 2017 (Fig. 2a; Table 2;

data source: USGS 2017), with a cluster around Rohtak. The focal mechanism solution of the earthquakes (Fig. 13; Shukla et al. 2007) shows epicenters of four earthquakes are lying on the MDF. Out of the previously studied focal mechanism solutions by Shukla et al. (2007), four of them suggest the associated faults are trending parallel to the MDF. However, all other's orientation do not coincide with that of the MDF, and hence may suggest the existence of other faults may be related and/or accentuated to lithospheric crustal loading of the Himalaya orogen on the Delhi-Sargodha Ridge (Dubey et al. 2012; Supplementary Fig. 3). Magnitude and frequency of occurrence of these earthquakes show an inverse correlation. Except for one earthquake, all other earthquakes occurred within 10–76 km depth. However, most of the earthquake

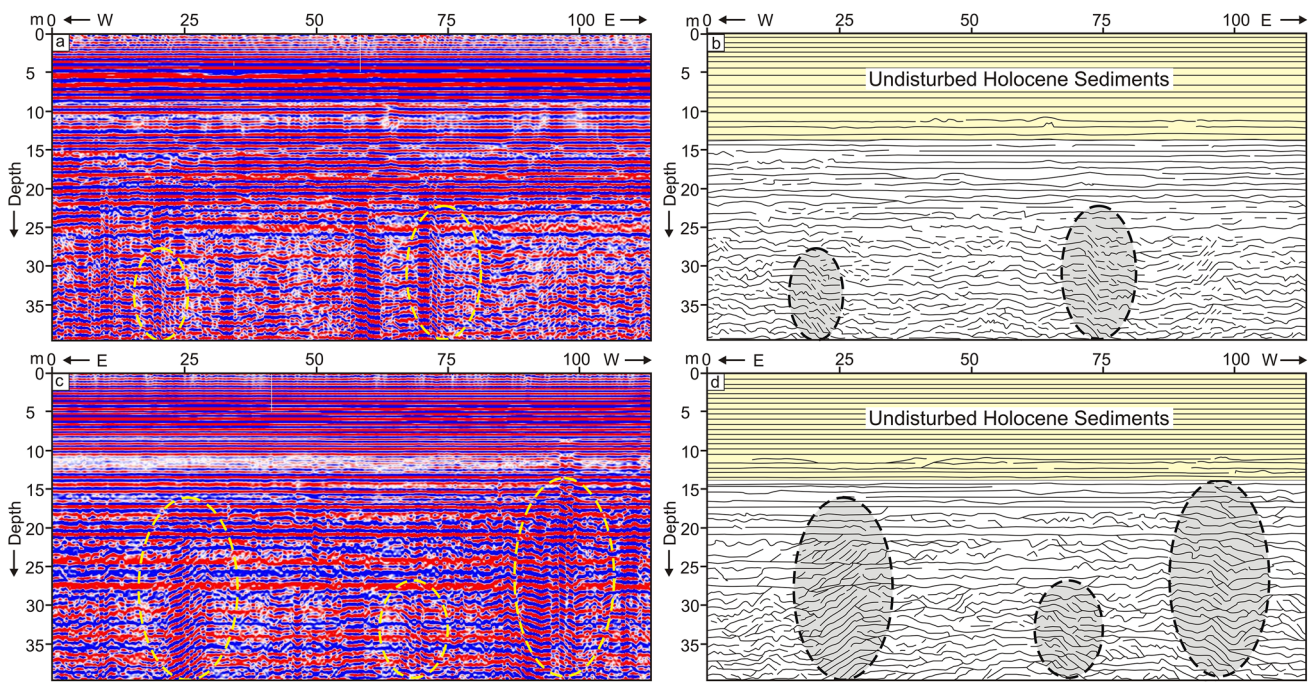


Fig. 12 a, c GPR profile across the MDF shows discontinuities in the shallow subsurface sediment layers and b, d Undisturbed Holocene sediments sequence and discontinuities surface redrawn from GPR profile

Table 2 Earthquake epicenter data around Mahendragarh–Dehradun Fault zone as obtained from USGS (<https://earthquake.usgs.gov>)

S. no	Date (DD-MM-YYYY)	Epicenters		Depth (km)	Mag-nitude (m_b)
		Latitude ($^{\circ}$ N)	Longitude ($^{\circ}$ E)		
1	06-11-1975	29.497	78.084	33	4.9
2	15-05-1990	29.178	76.73	33	4.1
3	15-11-1995	29.058	76.791	24.9	4
4	12-11-1996	29.919	77.172	53.7	4.5
5	30-03-1998	28.211	76.241	10	3.9
6	22-03-1999	29.257	76.94	207.6	4.1
7	28-02-2001	28.629	76.04	33	3.8
8	28-04-2001	28.588	76.841	10	3.7
9	13-09-2001	28.851	77.22	10	4.1
10	02-05-2002	27.696	75.81	33	4.1
11	27-07-2004	29.25	77.23	75.7	4.1
12	31-03-2006	28.976	76.606	10	3.9
13	07-05-2006	28.975	76.561	10	4.3
14	25-11-2007	28.555	77.057	10	4.7
15	16-08-2008	30.185	77.836	10	3.8
16	07-09-2011	28.724	77.189	10	4.3
17	05-03-2012	28.809	76.649	10	5.1
18	19-06-2012	28.728	76.685	10	4.1
19	20-12-2012	27.651	76.116	10	3.9
20	10-09-2016	28.7684	76.5733	10	4.1
21	16-11-2016	28.0012	76.7017	10	4.4
22	02-06-2017	28.9744	76.7797	10	4.7

m_b body wave magnitude

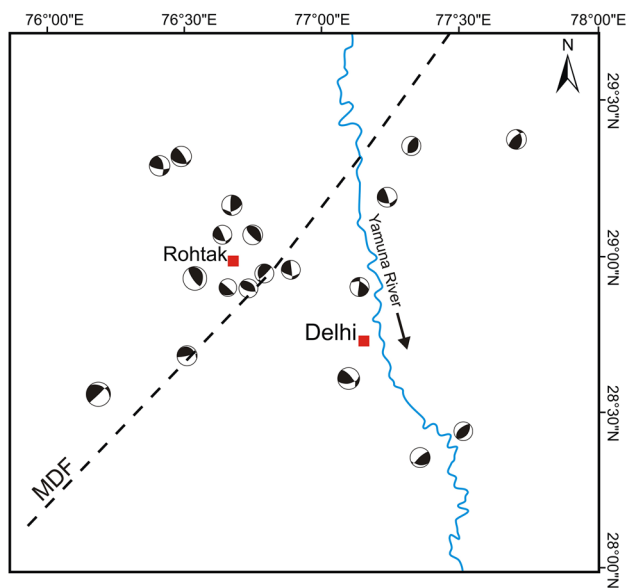


Fig. 13 Focal mechanism solutions of the seismic events along the MDF (Fault plane solutions data taken from Shukla et al. 2007)

hypocenters are confined in the basement within 10 km depth from the surface.

Discussion

Basement features of the Ganga plain

The basement of the Indian peninsula below the Ganga plain hosts many NE-SW trending basement ridges named from west to east as: the Delhi-Haridwar ridge, the Faizabad Ridge and the Munger-Saharsa ridge (Fig. 14; Patel et al. 2018; Godin et al. 2019). These ridges are the extension of the Indian peninsular shield through the Ganga basin

transverse to the Himalayan trend (Eremenko et al. 1968; Yin 2006; Godin et al. 2019). Prominent inherited basement faults (Godin et al. 2019) are running along the flanks of these basement ridges from Indian peninsular shield to the Himalayan front, and some of these are cross-cutting the Himalaya (Godin and Harris 2014) described as tear faults by Valdiya (2002). In addition to these, few other basement faults are also present in the Ganga plain following the trend of the basement ridges. These faults are interpreted to have been reactivated during the continental collision and formation of the Himalayan orogen (Valdiya 1976). Temporal reactivations of these basement faults since their development have been documented in the Permo-Triassic sedimentation cycles in the associated basins (Veevers and Tewari 1995). However, the reactivation history during the Paleozoic and Mesozoic is poorly documented due to limited rock exposure (Godin et al. 2019) and thick Late Cenozoic sedimentary cover on these faults. The edges of the basement ridges have been postulated to be seismically active (Dasgupta et al. 1987; Mugnier et al. 2017).

The MDF in this study demarcates the eastern boundary of the Delhi–Haridwar basement ridge and western boundary of the Shimla and Dehradun lineaments (Godin and Harris 2014; Godin et al. 2019). This lithospheric-scale feature possibly marks the contact between the Rajasthan and Bundelkhand cratons at depth (Mitra et al. 2011) and coincides with the subsurface change in crustal composition (Yin 2006). This basement feature may be capable of accommodating differential tensile deformation due to bending of the Indian plate as it underthrusts the Himalaya (Mitra et al. 2011). Similar deformation patterns are observed from geophysical data along the subduction zone in the northwestern and central Betic Cordillera (Ruiz-Constan et al. 2011) and Fiordland, New Zealand (Smith and Davey 1984; Reyners et al. 2002), that show tensile focal mechanism associated with the bending of the lithosphere. In addition, the NW–SE

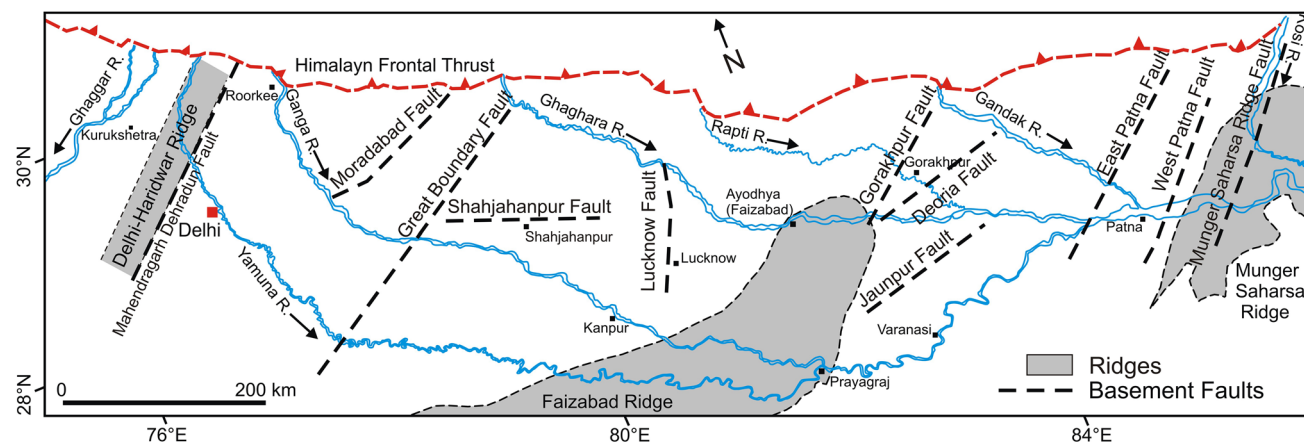


Fig. 14 Distribution of basement faults and basement ridges in the Ganga plain

trending peripheral flexural bulge of the Indian peninsula bordering the Ganga plain in its southern part, formed due to isostatic load of the Himalayan orogenic wedge, may also accentuates tensile deformations (Agrawal et al. 2002).

Seismicity around the MDF

Seismicity around the basement faults in the Ganga plain including the MDF is controlled by the Himalayan tectonics. The Himalaya is characterized by a series of south verging thrust splays branched off the MHT (Yin and Nie 1996; Powers et al. 1998; Gavillot et al. 2018). In this study, it has been observed that the southward thrust movements do influence the seismicity of the MDF and the peripheral bulge due to their preferred orientation to the thrust movement. The earthquakes associated around the MDF indicate evidence of being an active fault, which has implication for earthquake hazards assessments. Its position along the transition of the Ganga and Indus plains emphasizes the study regarding the behavior of the transitional margin fault to the ongoing tectonics. Similarly, its coincidence with the eastern margin of the Delhi-Haridwar subsurface basement ridge invites further studies along the buried basement faults in the Ganga plain. As this fault passes through the national capital Delhi, its seismotectonic evaluation is important regarding prediction of its seismic characteristics at different spatial and temporal scales in this highly populated region.

Earthquakes in the basement of the Ganga plain have different origin such as normal faulting at the flexural axis along the foreland bulge, reverse faulting within the basement blocks around the thrust uplift, and normal and/or oblique-slip motion along the basement fault-zone like the MDF. Bending of basement along the periphery of the basin due to thrust overloading (Supplementary Fig. 3) may be the source of earthquake clusters around the flexural bulge of the basement. The basement contour DEM (Fig. 15) suggests an NW–SE axial trend anticlinal high around Rohtak that may represent this flexural bulge, which is the probable extension of the Delhi-Sargodha ridge.

Focal mechanism solutions of previously studied earthquakes along the MDF support oblique-slip movement (Shukla et al. 2007). Irrespective of nature of the movement, basement faults in the Ganga plain show around a 30 km wide zone of surface deformation (Verma et al. 2017). However, the width of the zone is comparatively less around those faults developed along the basement ridges such as for the MDF.

In our study, geomorphic markers such as offset channels, initiation of new streams along the fault zone, elevation gradient in longitudinal channel profile that coincide with the subsurface projection of the MDF may suggest Quaternary fault activity. Geomorphic markers such as convergence of drainage, change in channel sinuosity are also potential

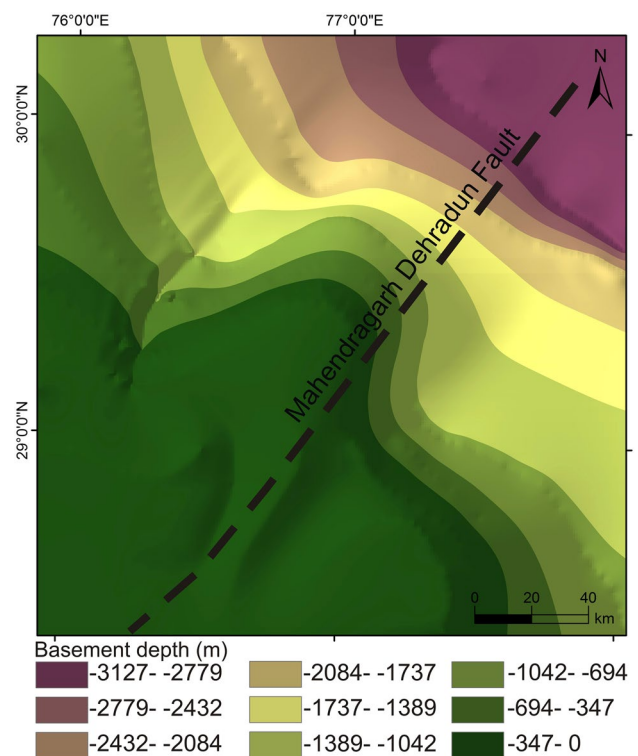


Fig. 15 Digital elevation model (DEM) of basement depth around the study area

geomorphic markers for both normal and reverse faults in the Ganga plain (Singh et al. 2006; Bhosle et al. 2009; Pati et al. 2011b, 2019). However, in this study these parameters did not provide convincing result about the presence of the fault. Sediment cover thickness, pre-existing basement structures, and bedrock channel lithology likely control lateral variation in channel response to local fault activity of the MDF.

Block tilting due to faulting is common in the Ganga plain (Mohindra et al. 1992; Pati et al. 2011a), which results in channel abandonment and migration to lower topographic level. Using ancient civilization sites continuity of paleochannels were marked around the MDF (Fig. 9). These paleochannels show an abrupt truncation at the MDF, which has been interpreted here as tectonically caused rather than climatically. OSL chronology of these paleochannels suggests 2.5–3 Ka of channel abandonment. The fault zone shows weakly developed soil as compared to the adjacent region (Fig. 10). Soils in either side of the fault zone show high solum thickness varies from 320 to 450 cm and well developed pedo-features whereas, in the fault zone soils show lesser development of pedo-features and thickness.

Available record of twenty two earthquakes around the fault establishes good correlations among the frequency of occurrence, depth and magnitude with time and space. The frequency of occurrence of the earthquakes around the MDF

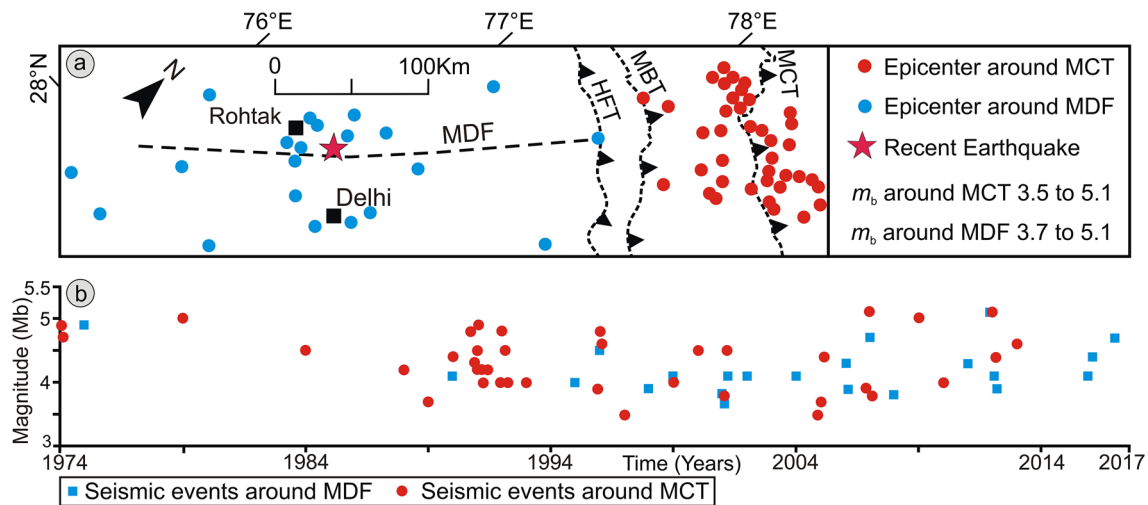


Fig. 16 **a** Earthquake epicenters along the MDF and MCT. **b** Time vs magnitude plot of earthquakes along the MDF and MCT

shows a major gap from 1975 to 1990. The earthquakes along the basement faults act as suitable avenues for stress transfer towards the stable craton from the active Himalayan front. The earthquakes clustered along the MHT projected along the main central thrust (MCT) within the time window (1975–2017) shows a positive correlation (Fig. 16). Periods marked by the occurrence of earthquakes along the MDF are also marked by seismically active period along the MHT and vice versa. This suggests a good temporal correlation among the Himalayan seismicity with that of the Ganga plain, particularly along the basement fault (MDF) and the peripheral bulge.

As no direct exposure of the fault is available, determining the fault kinematic is also difficult. GPR study brings out the presence of shallow-depth, near-vertical normal faults along the fault zone of the MDF. However, the strike-slip component cannot be determined from the 2-D GPR profile. Southward thrust movement of the Himalaya orogenic wedge would predict to impose strike-slip motion on orthogonal-oriented vertical basement faults, but the associated geology, geomorphology and the previously studied focal mechanism solutions suggest oblique-slip motion along the MDF. The present stress field configuration and the fluvial anomaly may suggest oblique-slip motion. This integrated approach provides several lines of evidence that suggest seismic activity near the MDF may exert surface deformation enhanced by regional stress of the Indian plate convergence with the Himalaya orogenic wedge. The area of study is part of the upper Ganga plain which has a thin sequence of Tertiary-Quaternary sediments with respect to its lower counterpart. Gawthorpe and Leeder (2000) explained the growth of the secondary faults associated with the basement

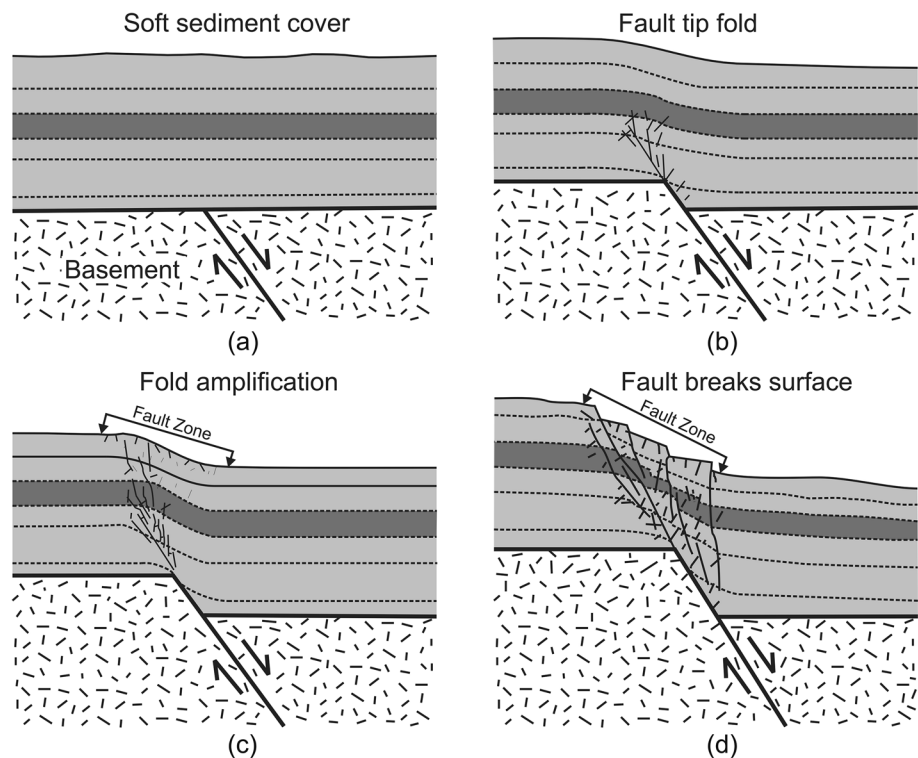
faults (Fig. 17) in a foreland basin. The MDF is manifested on the surface by forming a zone comprising one or more secondary faults leading to the change of topographic relief. The MDF and other nearby basement structures (peripheral bulge) are the sources of localized seismic activity near Delhi area, including the recent earthquakes in 2017, which may be linked to the quasi-synchronous Himalayan seismic cycle.

Conclusions

Based on GPR study, seismic analysis, fluvio-geomorphic characteristics, soil chrono-association, basement and terrain morphology around the MDF, the following conclusions may be drawn:

1. Seismicity around the MDF is quasi-synchronous with the Himalayan seismic cycle. It is probably the fact that southward thrust migration causes strain release along the basement fault and flexure on the peripheral bulge.
2. Tectonic geomorphological characteristics, GPR and the previously studied earthquake focal mechanism solutions suggest normal and oblique-slip motion along the MDF.
3. Associated channel morphology, soil chrono-association, and OSL chronology of the paleochannels across the MDF suggests that the fault is active since the Holocene.

Fig. 17 Upwards propagation of a basement fault through soft sediment cover (Redrawn from Gawthorpe and Leeder 2000)



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