Intraplate seismicity and earthquake hazard in the Aravalli–Delhi Fold Belt, India

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The Aravalli–Delhi Fold Belt (ADFB) is one of three prominent ridges on the continental part of the Indian plate extending northward from central India and subducting beneath the Himalayan arc. Though it is seismogenic along its entire NE–SW structural trend, activity varies spatially with a noteworthy region of higher seismicity in the vicinity of Delhi. We analyse historical and modern instrumented seismicity. Using recomputed focal mechanisms for events such as the 1956 Bulandshahr earthquake, we found that the maximum principal stress ($\sigma_1$) in this region is oriented in the N–S to NE–SW direction, similar to that in the neighbouring Garhwal–Kumaun Himalayas. Our analysis also indicates that the earthquakes along the ADFB occur on steep faults which are parallel or oblique to its NE–SW structural trend and that the entire crust appears to be seismically active as the earthquakes occur up to a depth of ~40 km. Within the better instrumented Delhi region, we observed a pattern in the average monthly frequency of earthquakes recorded that we speculate was modulated by monsoonal recharge of the local water table. The cause of seismicity in the AFDB is still a question for debate, pending better seismological and geodetic instrumentation, but we build on evolutionary models of the ADFB to suggest that seismicity is the consequence of the continued relative motion between the Bundelkhand and Marwar cratons in the northern Indian shield. The nature and causes of earthquakes in this region notwithstanding, the proximity of large cities such as Delhi, Jaipur and Udaipur to poorly-studied or unknown sources of seismic hazard is a concern and warrants further scientific and policy intervention.

Keywords. Intraplate seismicity; earthquake hazard; Aravalli–Delhi Fold Belt.

1. Introduction

Seismic hazard in India is dominated by earthquake processes along the Himalayan arc (e.g., Bilham 2019). This narrative has received further attention in recent years as more major and great earthquakes have been identified along the length of the Himalayan arc through palaeoseismic investigations (e.g., Malik et al. 2008), the analysis of historical seismicity (e.g., Ambraseys and Jackson 2003), and improved spatial estimates of geodetic strain accumulation (e.g., Stevens and Avouac 2015). However, the historical and instrumental records also point to infrequent but large and damaging earthquakes away from the Himalayan arc and within the intraplate setting of India.
peninsular India (e.g., Oldham 1883; Narula et al. 1996; Bendick et al. 2001). Such intraplate earthquakes are rare globally, accounting for barely 0.2% of the annual seismicity budget (Johnston 1996), and their retroactively identified causative faults exhibit long recurrence intervals (e.g., Rajendran and Rajendran 1999; Crone et al. 2003). However, despite their lower magnitudes and infrequent occurrences, intraplate earthquakes pose an almost similar hazard in some parts of the world due to higher population densities often coupled with poor hazard perception owing to the rarity of such earthquakes (England and Jackson 2011).

Within the intraplate setting of peninsular India, in addition to earthquake activity concentrated in regions of failed rifts, namely, the Kachchh, Narmanda–Son and Godavari rifts (Naqvi and Rogers 1987; Gangopadhyay and Talwani 2003; Sharma 2009), the Aravalli–Delhi Fold Belt (henceforth ADFB; figure 1) is the site of noteworthy seismicity. Moderate earthquakes have been well documented (figure 1) along the entire length of the ADFB from Gujarat through Rajasthan and in particular, in the vicinity of Delhi and the National Capital Region (henceforth Delhi–NCR). Sequences of felt earthquakes had often stoked concern in the Delhi–NCR, most recently in 2020, when over 30 earthquakes ($M_L > 1.8$) were recorded between April and August by the local network of National Centre for Seismology (NCS). In recent years, the influence of the ADFB on Himalayan earthquakes has also been discussed quite extensively (Gahalaut and Kundu 2012; Hetényi et al. 2016; Yadav et al. 2019; Dal Zilio et al. 2020), but our understanding of the seismogenesis within the ADFB itself is very limited. The 2011 Indian census indicates that the Delhi–NCR region alone is currently home to more than 28 million people. There are another five cities along the ADFB with individual population each in excess of half a million, such as Jaipur and Udaipur (figure 1). It is, therefore, of pressing concern that the mechanisms and processes that likely influence the seismic productivity in the ADFB are scrutinised in greater detail from a seismological and seismic hazard perspective.

In this article, we first review the geology and tectonics, historical and instrumental seismic history of the ADFB, re-evaluate the regional stress field using a well instrumented earthquake catalogue and focal mechanisms, and analyse the temporal variation in the occurrence of earthquakes to investigate the influence of precipitation on the seismicity in the northern ADFB. In light of these, we propose a hypothesis to explain ongoing seismicity in the ADFB influenced by the prevalent stress regime.

2. Geology and tectonics

Geographically, the Aravalli–Delhi Fold Belt (ADFB) is located in the northwestern Indian Precambrian shield (figures 1, 2). It is one of three prominent ridges (namely the ADFB, Faizabad and Munger–Saharsa ridges) on the continental part of the Indian plate and is thought to subduct beneath the Himalayan arc (Sastri et al. 1971; Rao 1973; Valdiya 1976). The ADFB also defines the Aravalli Mountain range that extends in a north–northeasterly trend towards the Delhi–NCR region from near the Gujarat–Rajasthan border ($\sim 24^\circ$N) in the south (figures 1, 2). The ADFB can be identified by the presence of the Palaeo-Proterozoic rocks of the Aravalli Supergroup (AS; figure 2) in the south that is overlain by Proterozoic rocks of the Delhi Supergroup (DS; figure 2); the DS extends along the entire length of the ADFB from Mount Abu in the south to the Delhi–NCR region in the north (see Gupta et al. 1980 for stratigraphic nomenclature). The ADFB unconformably overlies the Banded Gneiss Complex and the Barach Granite (BGC; figure 2) that outcrops to the east of the ADFB. The BGC is the oldest Archean cratonic nucleus of the western Indian shield (GSI 2011). Although the BGC is separated from the Bundelkhand Granite Massif (BGM) in the Bundelkhand Craton by Vindhyan cover rocks and the Great Boundary Fault (figure 2; Sharma 2009), they are thought to have undergone similar deformation events (Naqvi and Rogers 1987), shared similar geodynamic settings in the Proterozoic (Mondal and Ahmed 2001) and also have similar geochronological ages (Mondal 2003).

The ADFB is located within the Precambrian Indian Shield within the Aravalli (Naqvi and Rogers 1987) or the Rajasthan, or Rajasthan–Bundelkhand Craton (Sharma 2009). This craton is one of the nine Archean to early Proterozoic nuclei that constitute the Indian Shield (Naqvi and Rogers 1987). Vijaya Rao et al. (2000) further differentiated the Aravalli craton into the Bundelkhand and Marwar cratons (figure 2, inset). Based on interpreted structural features, such as the Jahazpur Thrust, and in combination with
lithological and geochemical evidence, Vijaya Rao et al. (2000) present a model for the evolution of the AFDB that involves differential motion between the Marwar Craton to the west and the Bundelkhand Craton to the east (Figure 2) between ~1800 and ~1100 Ma.

Surface and subsurface geological structures associated with repeated phases of rifting subduction and orogeny (e.g., Sychanthavong and Desai 1977; Sinha-Roy 1988; Sharma 1988; Sugden et al. 1990; Verma and Greiling 1995; Vijaya Rao et al. 2000) have been mapped along the length of the ADFB between Delhi and Mount Abu (e.g., Das 1988; Vijaya Rao et al. 2000; Mandal et al. 2018).

Deep seismic reflection images of the region along the Nagaur–Jhalawar profile that runs perpendicular to the strike of the ADFB clearly identify structural features such as the west-dipping Jahazpur Thrust and the Great Boundary fault that extend through the entire crust (Vijaya Rao et al. 2000; Mandal et al. 2018). The converging reflections within the ADFB and the presence of the ramp-flat structure of the Jahazpur Thrust confirm compression across the region (Vijaya Rao et al. 2000). Magnetotelluric (MT) measurements along the same profile also confirm the presence of the Jahazpur thrust in the region (Gokaran et al. 1995). The crustal depth in the Vindhyan basin is about 44 km,
and while the reflections are quite unclear below the ADFB, the crustal depth is slightly shallower here in comparison to that below the Marwar and Vindhyan basins (Mandal et al. 2018). Modelling of gravity data for crustal configuration also suggests the presence of high-density material in the ADFB (Mishra and Ravi Kumar 2014) and broadly confirms previous episodes of extension, rifting, deposition and convergence (Sharma 2009).

The extension of the ADFB beneath the Gangetic plains and the Himalayan arc as the Delhi–Haridwar ridge (figure 2) has been inferred, albeit poorly, by gravity (e.g., Godin and Harris 2014), seismological data (e.g., Arora et al. 2012; Gupta et al. 2013) and magnetotelluric studies (e.g., Lilley et al. 1981; Arora et al. 1982; Devi et al. 2019). Deformation of the Indo-Gangetic plains due to the ADFB ridge and its interaction with the Himalayan arc is also poorly understood in contrast with the extensively studied Munger–Saharsa Ridge (Duvall et al. 2020).

3. Historical and early-instrumental seismicity

The earliest known seismicity in the region of the ADFB preserved in manuscript form (Iyengar et al. 1999) describes a large earthquake and three
possible aftershocks around ~3000 BC in the Kurukshetra area (figure 1) during the Great War of the Mahabharata. Medieval Sanskrit manuscripts (Iyengar 1999) allude to shaking from earthquakes felt within our study area in the Arbuda, Kuru, Malwa, Maru, Matsya and Salwa regions (figure 1) between the 6th and the 11th centuries. In the larger region of the ADFB, contemporary compilations of seismicity (e.g., Oldham 1883; Chandra 1977; Srivastava and Ramachandran 1985) include accounts of numerous felt events collated from written colonial sources.

Historical earthquakes that were fatal and locally damaging struck Delhi on 26 July, 1720 and 10 December, 1835. Little is known about the 1835 earthquake aside for damage (intensity 6–7 EMS) north of Kashmiri Gate (figure 1, Inset B) and that there were an unknown number of casualties in Delhi itself (Bacon 1837). The 1720 earthquake is documented in Khafi Khan’s Muntakhab-al-lubab (Ahmed 1874; see translation in Iyengar 2000). This earthquake is assumed to have originated in the Garhwal–Kumaun Himalayas (Ambraseys and Douglas 2004), but for this argument, there is no supporting evidence. Instead, Khafi Khan’s eyewitness account describes severe damage (Grade 3+; Grünthal 1998) from Kabuli Gate to Lal Darwaza, including the collapse of part of the Fatehpuri Masjid (figure 1, Inset B). This equates to a macroseismic intensity of >7 EMS using the European Macroseismic Scale (EMS; Grünthal 1998). He also writes that daily aftershocks were numerous in the first month but that these dropped off in number over the next five months. We believe this is indicative of an aftershock sequence from a local source. Singh et al. (2013) gave the correct date (22 Ramzan 1132 Al Hijri = 26 July, 1720) for this event. Many authors including Oldham (1883), list an incorrect date (15 July, 1720) from an incorrect calendric conversion.

The largest known earthquakes in the southern ADFB occurred in 1848 and 1882. For the 26 May 1848 earthquake, we calculate $M_I \approx 5.8 \pm 0.7$ (1σ) using an intraplate intensity attenuation model determined by Szeliga et al. (2010). This earthquake at 23:00 LT destroyed buildings at Anadra, where one person was killed (figure S1a; table S1a in Supplementary material 1; Bombay Times and Journal of Commerce, 7 June 1848; 10 June 1848). The Dilwara temples were damaged and another fatality occurred when part of the Gaumukh Temple collapsed south of Mount Abu (Bombay Telegraph, 7 June 1848). The strongest aftershock (table S1b in Supplementary material 1) occurred at 1 AM local time on 27 May 1848 for which we estimate $M_I \approx 4.8 \pm 0.6$ (1σ). For the 15 December 1882 earthquake (figure S1b; table S2 in Supplementary material 2), we estimate $M_I \approx 5.7 \pm 0.6$ (1σ). This earthquake damaged buildings in the Deesa–Mount Abu region with the loss of five lives at Donar in north Gujarat (Bombay Gazette, 20 December 1882).

Other significant earthquakes that occurred near the southern extremity of the AFDB near the Deesa-Mount Abu area are on 9 October 1875 (Hunter et al. 1909) and 15 August 1906 (Walker 1907; Ambraseys 2000). The 15 August 1906 earthquake (figure 1) was felt in parts of north Gujarat, Rajastan and Sindh (Ambraseys 2000); at Abu Road, it was so severe that an eyewitness ‘could scarcely walk across the floor’ (Bombay Gazette, 20 August 1906). Ambraseys (2000) places this event in the Thar desert and computes $M_W \sim 6.2$.

It is important to note that a succinct account from Khanapur (Oldham 1883) in the Bulandshahr area near the northern ADFB (figure 1) on 24 October 1831 is suggestive of a large 19th century earthquake in the western Gangetic doabs. However, new archival data that we found (table S3 in Supplementary material 3) points to a much more extensively felt earthquake in north India (figure S1d), but the lack of a locus of high intensity renders it difficult to isolate an epicentral region. We note that further work is needed to conclusively pin down its origin.

On the contrary, a substantial body of historical materials (see Dasgupta and Mukhopadhyay 2014) supports a source for the so-called ‘Mathura earthquake’ (e.g., Chandra 1977; Srivastava and Jalote 1977) of 1 September 1803 earthquake in the Garhwal–Kumaun region (figure 1). Neither did this originate near Mathura, nor is there evidence that a separate earthquake occurred at Mathura (figure 1) as suspected by contemporary authors (e.g., Srivastava and Jalote 1977).

4. Instrumented seismicity: Spatial and temporal variation

We compiled a dataset of instrumentally detected earthquakes in the ADFB region (figure 3) from 1960 to 2020, using local catalogues compiled by both the NCS and the India Meteorological Department. After removing duplicates, we
supplemented this dataset with teleseismic locations from the International Seismological Centre (ISC) for larger events. Although data on historical seismicity of the central ADFB is sparse, the IMD (now the NCS network) detected earthquakes larger than $M_L > 4$ along the length of the ADFB between Delhi and Udaipur.

A large cluster of earthquakes is evident to the northwest of Delhi (within an area of $\sim 100 \times 100$ km$^2$) that encompasses the Rohtak–Sonepat region in Haryana. This cluster includes the 27 August 1960 earthquake with an epicentral region in Gurugram (formerly Gurgaon). Its magnitude is commonly assumed to have approached $M \approx 6.0$ (e.g., Tandon and Srivastava 1974; Szeliga et al. 2010). However, a later thorough analysis of regional waveforms and intensity observations concluded that the magnitude did not exceed $\sim M_W 4.9$ (Singh et al. 2013). Outside the Delhi–NCR region, the 10 October 1956 Bulandshahr (also Bulandshahar) earthquake (figure S1c) is the strongest earthquake near the immediate northern extent of the AFDB. It caused significant damage to villages between Khurja and Bulandshahr, with the loss of over 29 lives (Times of India, 21 October 1956).

The temporal variation of instrumented earthquakes in the ADFB shows low seismicity prior to $\sim 1994$, with maximum magnitude of $\sim 5.6$ (figure 4). However, this apparent period of lower activity is a consequence of a lower threshold of instrumental detection being $M_L > 4$. Ten observatories in the Indian seismological network were upgraded to the Global Seismic Network (GSN) standard in the 1990s (Bhattacharya and Dattatrayam 2000). As a result, between 1994 and 2000, the frequency of earthquakes being detected also increased by way of improved monitoring, and in particular, a lowering of the instrumental threshold to $M_L 3.4$ for reliable event detection. The frequency of earthquake detections has significantly improved since 2000 (Bhattacharya and Dattatrayam 2000). Using the compiled dataset of 629 earthquakes, we computed a magnitude of

Figure 3. Epicentral distribution of earthquakes ($M \geq 2.5$) in the ADFB since 1966 (NCS/IMD). Size of the circles denotes the magnitude as per the scale shown in the inset. Focal depth estimates of the earthquakes are shown by colour with scale on the bottom right. Black stars are earthquakes of moderate to strong magnitude. Their year of occurrence is also indicated. Current locations of the national seismological stations of the National Centre for Seismology (NCS) are also shown. MDF: Mahendragarh–Dehradun Fault; MF: Moradabad Fault; GBF: Great Boundary Fault; JT: Jahazpur Thrust.
completeness ($M_C$) of $M_L 2.2$ for the ADFB (figure S2 in Supplementary material 4) for earthquakes after 2000. However, to ensure the completeness of the earthquake catalogue, we use a more conservative $M_C$ estimate of $M_L 2.5$ in all our figures and analysis. It is surprising to note that the earthquake frequency ($M \geq 2.5$) appears to have decreased after 2012, but this is most likely due to a change in criterion in magnitude estimation. However, despite this change, there is no evident change in the frequency of earthquakes greater than $M_L 3.5$ (annually averaging $\approx 5$ per year) since the year 1998 in the region (figure 4). Periods of temporal clustering in earthquakes can also be noted in these plots, for example, in 2010, 2013, and 2019 (figure S2c). We also take this opportunity to conjecture that the magnitudes of earthquakes prior to 1998 (figure S2c) appear to have been systematically overestimated by $\approx 0.5$ units of magnitude due to the use of older, analogue instruments. As the focal depth of most of these earthquakes in the ADFB extends up to $\sim 40$ km (figure 3), the entire crust, as deduced from seismic reflection data (Vijaya Rao et al. 2000; Mandal et al. 2018), appears to be seismogenic.

We also investigated these data for any seasonal variability in the seismicity. In our analysis of monthly seismicity ($M_L \geq 2.5$) over the past 50 years in the Delhi region, we find that the monthly earthquake frequency shows a bimodal distribution (figure 5). The number of earthquakes from March to May and later between September and November was greater than the number recorded from June to August and also from December to February; most conspicuous was the relatively lower number of earthquakes recorded during the month of August. The bimodal distribution showing an increase in frequency in April and November (frequency higher than the mean $+1$ standard deviation) and a decrease in frequency in August and December is certainly significant (frequency lower than the mean $-1$ standard deviation). Intriguingly, this minimum in August (figure 5) coincides with the highest precipitation during the monsoon (Kothawale and Rajeevan 2017). This apparent correlation implies that the seasonal rainfall must modulate earthquake productivity due to the percolation of rainwater and/or the recharge of the ground water table as elsewhere (e.g., Hainzl et al. 2006, 2015; Sharma et al. 2020).
that the polarities at Kiruna, Matsushiro and data from Indian and global stations. We found = 72 derived by Tandon (1975) for the 1956 Bulandshahr, 1966 Morabadad, ADFB, i.e., 1956 Bulandshahr, 1966 Morabadad, the three largest instrumented earthquakes in the addition to the B waveform modelling recorded at a single station in reliable than the others as they were derived using Verma 2012). The vast majority of these earth- B Bansal et al. 2007; Bansal et al. 2010; Bansal and Verma 2012). The vast majority of these earth- quakes are from the Delhi region. The nodal planes of these focal mechanism solutions show large variations in strike, dip and slip direction. Of these, we consider the three focal mechanism solutions by Bansal et al. (2009) and Singh et al. (2010) more reliable than the others as they were derived using wavefield modelling recorded at a single station in addition to the first-motion polarity data.

We also re-examined the focal mechanisms for the three largest instrumented earthquakes in the ADFB, i.e., 1956 Bulandshahr, 1966 Morabadad, and 1969 Mount Abu. A focal mechanism was derived by Tandon (1975) for the 1956 Bulandshahr earthquake (strike (φ) = 103°, dip (θ) = 72°, rake (λ) = 168°, figure 5) using first-motion data from Indian and global stations. We found that the polarities at Kiruna, Matsushiro and Uppsala (all compressions), and at Bokaro (di- lation) in original station bulletins (see Data and resources) are inconsistent with the polarities listed by Tandon (1975). Both Tandon (1975) and the ISC bulletin list a compression at Dehradun but this is not to be found in the original Indian seismological bulletin. Factoring in these corrections, we re-evaluated the mechanism for this earthquake (φ = 190°, θ = 80°, λ = 65°, figure 6).

Focal mechanisms were derived by Chandra (1977, 1978) for the 1966 Moradabad (φ = 101°, θ = 30°, λ = −90°) and the 1969 Mount Abu (φ = 128°, θ = 54°, λ = 135°) earthquakes from the P-wave polarities at teleseismic distances. Chouhan (1975) also provided focal mechanism solutions for the 1956 Bulandshahr (φ = 3°, θ = 62°, λ = −27°) and 1966 Moradabad (φ = 358°, θ = 76°, λ = −29°) earthquakes, both of which indicate predominantly strike-slip motion with a normal component. However, we do not consider Chouhan’s (1975) mechanisms as these were constrained by fewer polarity phases. We found an additional five polarities (all compressive) for the 1966 earthquake reported in the Indian seismological bulletin for 1966 (see Data and resources) for BOM (Mumbai), DDI (Dehradun), KOD (Kodaikanal), PBA (Port Blair) and POO (Pune). The polarity notation at BOM is unclear in the original bulletin, but we assume it to be a compression given its proximity (~117 km) to POO with a similar azimuth and an almost similar epicentral distance. We also note that at the time of writing in January 2022, the online ISC page for this event (ISC ID: 844491) indicated both compression and dilatation at POO for two separate P-phases (Pn and pP), which conflicts with the compressive polarity recorded in the original Indian seismological bulletin for 1969 (see Data and resources) which is also repeated in the printed ISC bulletin itself (ISC 1970). For the 1969 Mount Abu earthquake as well, we add further five first-motion polarities from BOM, NDI (Delhi), and PBA; all dilatations except at PBA. Once again, at the time of writing, the compressive polarity reported for NDI by the online ISC page (ISC ID: 803720) for this earthquake conflicted with a dilatation recorded in the Indian seismological bulletin for 1969 (see Data and resources). In the case of the 1966 and 1969 earthquakes, the additional first-motion observations do not change the solutions derived by Chandra (1977, 1978).

We inverted the 26 available focal mechanism solutions (Shukla et al. 2007; Bansal et al. 2009;
Singh et al. 2010; Bansal and Verma 2012), including those for the 1956 Bulandshahr and 1969 Mount Abu earthquakes re-evaluated in this study, to estimate the direction of principal stresses (figure 6) by STRESSINVERSE (Vavryčuk 2014), which is a non-linear joint inversion scheme for stress and fault orientations. We exclude the 1966 Moradabad earthquake from our analysis as the normal slip evident in its focal mechanism is likely to be due to the Himalayan arc parallel flexure of the Indian plate (Bilham et al. 2003), similar to outer rise earthquakes in subduction zones, rather than processes associated with the ADFB. Moreover, it is distinctly different from the focal mechanism solutions of the Delhi–Aravalli region. Our inversion yields the azimuth and plunge for \( \sigma_1 \) as 39° and 0° (±21°) for \( \sigma_2 \) as 309° and 9° (±24°) and for \( \sigma_3 \) as 131° and 81° (±16°) (black arrow in figure 7; figure S3 in Supplementary material 4). The orientation of \( \sigma_1 \) is closely aligned with the structural trend of the ADFB and is not conducive to slip on planes of weakness parallel to the strike of the ADFB. However, this stress orientation is conducive to faulting on planes which are oblique and transverse to the strike of the ADFB. The direction of \( \sigma_1 \) is also consistent with the India–Eurasia convergence direction (DeMets et al. 1990) and with the convergence in the adjoining Garhwal–Kumaun region (Yadav et al. 2019). We also inverted the reliable focal mechanisms (at Sl. no. 2, 20, 21, 22 in table S4 in Supplementary material 4) separately; though there are only four such focal mechanisms to provide any reliable estimate of stress regime, their inversion yields the azimuth and plunge for \( \sigma_1 \) as 17° and 23° (±33°), for \( \sigma_2 \) as 278° and 19° (±41°) and for \( \sigma_3 \) as 152° and 59° (±35°) (Grey arrow in figures 7, S3 in Supplementary material 4). The results of the analysis are based on only four focal mechanism solutions and hence are not well constrained. Nevertheless, the obtained stress regime is generally consistent with that obtained from all focal mechanism solutions.

6. A hypothesised tectonic model for seismogenesis in the ADFB

In light of our scrutiny of historical and instrumental seismicity in the AFDB, and our analysis of the stress regime, it is necessary to contemplate the reason for the seismicity in this intraplate region. There are two essential requirements for the occurrence of earthquakes associated with tectonic processes: (i) the presence of optimally oriented faults to slip during earthquakes and (ii) relative motion across these faults to cause strain to accumulate on them. In addition to the regional stress field generated by ‘ridge push’ (Richardson et al. 2010;
other factors that produce local strain accumulation and add to the tectonic stress field include volumetric heterogeneities such as variations in intraplate lithospheric thickness (e.g., Campbell 1978; Zoback et al. 1985), the presence of hydrothermal fluids expelled during early geological periods that assist triggering by reducing normal stresses (e.g., Sibson 1996; Miller et al. 2004; Jamtveit et al. 2019) and isostatic glacial rebound (e.g., Wu and Johnston 2000). In the context of the Indian plate, the flexure of Indian plate due to the India–Eurasia collision and strong locking at the Main Himalayan Thrust (MHT) may also add to the stress regime in the Indian plate (Coblentz et al. 1998; Copley et al. 2010), at least in the neighbouring region of the Himalayan arc. Intraplate seismicity, as a result of these, is largely concentrated along zones of weakness namely rifted margins (e.g., Wolin et al. 2012), interior failed rifts or aulacogens (e.g., Johnston 1996), and in mobile belts along the margins of cratons (e.g., Craig et al. 2011; Sloan et al. 2011). In the context of our study, the ADFB falls in the latter category. It is inferred to have been formed by alternating phases of rifting, deposition, and convergence between the Bundelkhand and Marwar cratons which led to the development of the Aravalli suture (~1800 Ma) and lithologies of the Aravalli fold belt, and later the Delhi suture (~1100 Ma) and the lithologies of the Delhi fold belt with the BGC juxtaposed in-between the two (Vijaya Rao et al. 2000).

Expanding on the geological evolutionary model proposed by Vijaya Rao et al. (2000), and to produce the stress regime consistent with the fault plane solutions and our stress inversion results, we hypothesise that the Marwar and the Bundelkhand cratons continue to move with different velocities with respect to each other and that the difference in the rate of motion could be as small as a fraction of an mm/year. Such a motion could also be due to the difference in resistive force on the MHT in the two Himalayan arc segments (either due to difference in convergence rate or due to difference in locking on the MHT) north of Marwar and...
Bundelkhand cratons. We also hypothesise that the relative motion of the Marwar Craton should be slower with respect to the Bundelkhand Craton which in turn would facilitate the expected slip on structures within the ADFB (figure 8). Also, a slower moving Marwar Craton would lead to compression across the Kachchh failed rift (figure 8), which would be consistent with the GPS measurements across the Kachchh failed rift (Gahalaut et al. 2019).

We acknowledge that, critically, the current lack of geodetic measurements across the ADFB severely limits the quantitative testing of our hypothesis. This is crucial since our hypothesis may imply that the ADFB should be just as active as the Kachchh rift, which is perplexing given the low seismicity we have documented over the past two centuries within the ADFB. We put forward three possible explanations.

(i) Temporal clustering over geologic time periods: It is likely that both the ADFB and the Kachchh rift are comparable in terms of earthquake activity over longer time scales and that, akin to other intraplate settings (e.g., Li et al. 2009; Stein et al. 2009; Clark et al. 2015), they are both currently experiencing phases of quiescence and renewed activity, respectively.

(ii) Aseismic differential motion of ADFB-bounding cratonic blocks: Alternatively, we suggest that the relative motion between the Bundelkhand and Marwar blocks is occurring largely aseismically in contrast to the Kachchh paleo-rift.

(iii) Differential geologic age: Another plausible explanation is that the Proterozoic age of the ADFB predates the cessation of rifting in both the Kachchh and Narmada–Son rifts. The Late Triassic to Late Cretaceous Kachchh and Narmada–Son rifts are geologically younger and are more active owing to greater mass heterogeneity and the presence of metamorphic fluids in this region as compared to that in the ADFB.

Each of these explanations warrant closer investigation, and even though we are partial to the third possibility, this could plainly be conjecture on our part. These questions can only be answered in the future from improved geodetic and seismic instrumentation in the region of the ADFB.

7. Discussion

The significantly lower magnitude and frequency of modern seismicity within much of the Proterozoic Aravalli–Delhi Fold Belt (ADFB) in comparison to the adjacent Delhi and Kachchh regions has meant that there has been little scientific focus on this region from a perspective of seismic hazard. As a consequence, the current and future seismic potential of the ADFB from Delhi to Mount Abu is poorly constrained. With this in mind, we have attempted to understand the ADFB by analysing available documentary material (e.g., Ahmed 1874) and instrumental observations for the last two centuries illuminating seismicity. We also propose a first-order hypothesis for seismogenesis along the length of the ADFB in an attempt to understand what drives earthquake activity in this part of the Indian Shield. The forces that govern intraplate seismicity are undoubtedly complex and numerous (see Wolin et al. 2012), and our interpretation is constrained by geological observations and a recomputed stress field derived from seismological data. Surprisingly, the faults of this Proterozoic fold belt which are well developed and exhibit clear geomorphic expressions on the eastern flank of ADFB (Mandal et al. 2018), are not associated with seismicity. Instead, seismicity appears to occur on poorly mapped or unmapped faults.

Figure 8. A schematic cartoon showing the Marwar and Bundelkhand cratons modified after Vijaya Rao et al. (2000). Thin and short lines around Delhi represent various seismogenic faults. The Marwar Craton is hypothesised to move more slowly than Bundelkhand Craton, causing sinistral motion across ADFB and oblique motion on faults, which are transverse to the ADFB, which adds to the compression across the Kachchh paleo rift (shown by southward arrows), making it seismically very active.
along the western flank of the ADFB. We acknowledge that our hypothesis is limited by the paucity of seismological observatories and thereby, lack of focal mechanisms for earthquakes between Delhi and Udaipur. We also note that the paucity of GPS monitoring sites in Rajasthan and central India renders it impossible to quantitatively test our hypothesis using GPS measurements. We hope that our study fuels further scientific investigations to identify, interpret and analyse geological structures that are potentially active or bear the potential for reactivation in the current stress regime. We are also hopeful that it will facilitate the establishment of denser seismological and geodetic instrumentation arrays in the region.

While earthquake activity is low in the southern ADFB and sporadic in the central ADFB, a noteworthy cluster of seismicity is observed in the Delhi region in the north (figure 3). The instrumental detection of these earthquakes is a consequence of modern instrumentation (Bhattacharya and Datatrayam 2000; Srivastava et al. 2005). We believe that the density of this network has made it possible to lower the detection threshold of smaller magnitude earthquakes within this region. However, in comparison to the 17 stations in the Delhi region, there are currently only two seismological stations, i.e., Ajmer (AJMR) and Udaipur (UDPR), located with the ADFB (figure 3) that provide coverage for the central and southern ADFB. As a consequence of this sparse network, it is likely that many smaller earthquakes within the central and southern ADFB have remained undetected by the national backbone network. It is also highly probable that for many smaller events, only limited phases were automatically detected at single stations within Rajasthan, and therefore their locations and magnitudes remain unknown. It is, therefore, likely that the cluster of seismicity in the Delhi region might represent a network bias. But this needs to be tested with a uniform dense network in the ADFB, as in the southern extreme of the ADFB. Choudhury et al. (2019) reported higher activity based on the earthquake data of 2006–2017 from the local network in Kachchh and Saurashtra region. However, even in their case, the network does not cover the ADFB or even its southern part. Nevertheless, reported higher seismicity in Delhi region, in turn, leads us to question whether the cluster of seismicity is independent of the ADFB or whether it is representative instead. Within this cluster, we have hypothesised that seismicity could be linked to the withdrawal of ground water and the subsequent depletion of the water table which is indicated by the existence of a relationship between the monthly frequency of earthquakes and rainfall during the annual monsoon (figure 5). It is now well established that large parts of the Gangetic plains (which include the states of Haryana, Punjab and Uttar Pradesh) experience a severe depletion of groundwater table due to excessive ground water withdrawal for agriculture and urban needs (see Rodell et al. 2009; Tiwari et al. 2009; MacDonald et al. 2016; Mishra et al. 2018). Tiwari et al. (2021) explored this possibility and suggested that this decrease in internal load may add stress to the faults by unclamping them, i.e., reduction of normal stress, leading to an increase in the frequency of earthquakes similar to that discussed previously in this article while explaining the seasonal variability of seismicity. The presence of a seismicity cluster in the Delhi region is, however, curious as there is no indication of similar clusters of seismicity occurring elsewhere within the Gangetic plains. One reason for this might be that the faults in the Delhi region are optimally oriented for failure with respect to the ambient stress direction leading those that are critically stressed to produce earthquakes. The varied focal mechanisms of earthquakes in the Delhi region (Shukla et al. 2007; Bansal et al. 2009; Singh et al. 2010; Bansal and Verma 2012) could be suggestive of a dynamic environment wherein stress is transferred from critically stressed and optimally oriented faults to other structures as has been observed in the Koyna–Warana region in Maharashtra in western India (Gahalaut et al. 2004). They may also indicate the heterogeneity in the ADFB in terms of fault orientation and slip within it. We infer that this implies the earthquakes in the ADFB generally occur on planes that are transverse or oblique to the NNE–SSW strike of the ADFB. This is in line with our stress inversion analysis discussed in this section. Alternatively, these focal mechanisms may not be well constrained. Undoubtedly, the true solution to these hypotheses would be best determined by improving the density of seismological stations in the ADFB and as a matter of practicality, nationwide in India.

The clustered seismicity in the Delhi region is often associated with elevated public concern. Although the number of earthquakes detected in 2020 might appear to have warranted this attention, it is important to bear in mind that the annual average number of earthquakes in the region...
> M_L 2.5 and M_L 3.5 and above are ∼25 and ∼5, respectively. In 2020, thirty-one earthquakes of magnitude M_L > 1.8 were detected in this region until September 2020, of which 15 were above M_L 2.5 (which is the lower magnitude threshold of the NCS catalogue) and three were above M_L 3.5. In other words, the rate of seismicity in 2020 was well within the level of background seismicity for this region. In fact, in terms of the number of earthquakes in these magnitude bins, there were fewer earthquakes in 2020 (until September) than in an average year. Many of the shocks in 2020 also coincided with reduced public mobility from curfews during a stringent nationwide lockdown across India during the early months of the Covid-19 pandemic. As a result, these earthquakes were more widely perceived and also garnered more attention in the press and on social media than they would have in previous instances owing to an already heightened sense of public angst and uncertainty. The epicentres of these earthquakes are also not tightly clustered in space but are within a 100 × 100 km^2 region that overlaps with the northern ADFB (figure 3). We have also drawn attention to similar episodes of activity in the same region in 2010, 2013, 2017 and 2019. As a crucial caveat, we add that given the current unpredictable status of earthquakes and the short instrumental record in this region, it is currently impossible to ascertain whether the ongoing earthquake activity is precursory in nature.

The northern ADFB is much better studied, given its proximity to the Delhi region, which has been the focus of many seismic hazard studies (e.g., Iyengar 2000; Singh et al. 2010; Mandal et al. 2014) and is also better instrumented. A long history of political and economic prominence of the Delhi region meant that some form of a written record, albeit biased by political considerations, extends several centuries into the past. More contemporary records show that local or regional earthquakes since the beginning of the 19th century have damaged the city in 1835, 1956, 1960, and 1966. The most significant of these was the 27 August 1960 earthquake that caused significant damage in the Gurugram area and is well documented by Nath et al. (1968). On the other hand, known damage from the 1720 earthquake derived from Khafi Khan’s eyewitness description in the Mun-takhab-al-lubāb is significantly worse than the damage caused by the earthquakes mentioned before, including the 1960 Gurugram earthquake. For the intensities (>7 EMS) inferred from his description, a Kumaun–Garhwal earthquake should have exceeded M > 8.5 based on the predicted decay of intensity in north India (Ambraseys and Douglas 2004; Szeliga et al. 2010). While this scenario is entirely within the realm of possibility, accounts of damage caused by the earthquakes mentioned before, including the 1960 Gurugram earthquake.
motion. As the focal depth of earthquakes extends up to \( \sim 40 \) km, we infer the entire crust to be seismogenic. Within the Delhi region, the observed seasonal variation in the annual frequency of seismicity appears to imply that they are influenced by monsoonal precipitation that clamps (or unclamps) preferentially oriented faults. We also note that while the Delhi region experienced a fair number of earthquakes in early to mid-2020, this seismicity was within the range of background seismicity. Building on this point, we also note that the current activity might not be considered precursory, as such clustered activity in time in the ADFB has occurred on several occasions in the past. Based on both historical documentation and modern instrumental records, the possibility of future moderate magnitude earthquakes cannot be ruled out in the ADFB region. This underscores the need to improve the seismic network uniformly, along and in regions adjacent to the ADFB to ascertain whether earthquakes occur all along the ADFB and whether the seismicity in the Delhi region is anomalous or not. A more careful and thorough analysis of the archived literature will also help in identifying past earthquakes with as much quantification as possible. It is also important to undertake comprehensive geophysical studies (particularly the detailed mapping of subsurface structures and quantification of crustal strain using GNSS) to understand the seismogenecis within the ADFB, given its proximity to densely populated urban centres such as Delhi, Jaipur and Udaipur.

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Data and resources

Digital metadata used in figures 1 and 2 were downloaded from Bhukosh (http://bhukosh.gsi.gov.in/) and later versions of geological maps were downloaded from the Geological Survey of India repository (https://www.gsi.gov.in). Seismological bulletins for 1956, 1966, and 1969 are available from the ISC-GEM project (http://storing.ingv.it/bulletins/ISC-GEM). Earthquake data from the National Centre for Seismology are available at seismo.gov.in. The Persian text of the Muntakhab-al-lubāb including folio 883 relevant to the 1720 earthquake can be accessed freely at the Panjab Digital Library (http://panjabdiliglib.org/). Tabulated summaries of newspaper accounts for the 1848 (table S1a, b), 1882 (table S2), and 1831 (table S3) earthquakes discussed in the text, and a table of focal mechanisms (table S4) can be found in the supplementary material to this article. Newspapers and historical sources scrutinised in this study were consulted digitally or in person at the Asiatic Society of Mumbai, the British Library (London), the Australian National University and the National Library of Australia.

Author statement

V K Gahalaut initiated the discussion on Delhi earthquakes and all authors jointly conceptualised the problem. R K Yadav analysed seismicity and did stress inversion. S S Martin detailed the historical seismicity from various newspaper reports and literatures. All authors participated in interpreting, writing and reviewing the article.

References

Ahmed K A 1874 The Muntakhab-al-lubāb of Khān Khān, Bibliotheca Indica, Asiatic Society of Bengal, Part II, Kolkata, 883p.
Ambraseys N N 2000 Reappraisal of north Indian earthquakes at the turn of the 20th Century; Curr. Sci. 79(9) 1237–1250.
Gokaran S G, Rao C K and Singh B P 1995 Crustal structure in southeast Rajasthan using magnetotelluric techniques; In: Continental crust of NW and Central India, Geol. Soc. India Memoir 31 373–381.

Grünthal G (ed.) 1998 The European macroseismic scale EMS-98, Vol. 15, Conseil de l’Europe, Cahiers du Centre Européen de Geodynamique et de Seismologie, Luxembourg, 101.

GSI 2011 Geology and mineral resources of Rajasthan; Geol. Surv. India, Misc. Publ. 30(2) Kolkata, 130p.

Gupta S N, Arora Y K, Mathur R K, Iqbaluddin B P, Sahai T N, Sharma S B and Murthy M V N 1980 Lithostatigraphic map of Aravalli Region (1:1000,000); Geol. Surv. India, Calcutta.

Gupta A K, Chopra S, Prajapati S K, Sutar A K and Bansal B K 2013 Intensity distribution of M 4.9 Haryana border earthquake; Nat. Hazards 68 405–417, https://doi.org/10.1007/s11069-013-0638-6.

Hainzl S, Kraft T, Wassermann J, Igel H and Schmedes E 2006 Evidence for rainfall-triggered earthquake activity; Geophys. Res. Lett. 33 L19303, https://doi.org/10.1029/2006GL027642.

Hainzl S, Aggarwal S K, Khan P K and Rastogi B K 2015 Monsoon-induced earthquake activity in Talala, Gujarat, India; Geophys. J. Int. 200(1) 627–637, https://doi.org/10.1093/gji/ggv421.

Heidbach O, Rajabi M, Reiter K, Ziegler M and WSM Team 2016 World Stress Map Database Release 2016. V. 1.1. GFZ Data Services, https://doi.org/10.5880/WSM.2016.001.

Hetényi G, Cattin R, Berhet T, Le Moigne N, Chopheel J, Lechmann S, Hammer P, Drupka D, Sapkota S N, Gautier S and Thinley K 2016 Segmentation of the Himalayas as revealed by arc-parallel gravity anomalies; Scientific Reports 6 33866, https://doi.org/10.1038/srep33866.

Hunter W W, Cotton J S, Burn R and Meyer W S 1909 The Imperial Gazetteer of India; Oxford.

International Seismological Centre (ISC) 1970 Bulletin of the International Seismological Centre, August 1–16, 1966, Edinburgh, pp. 198–200.

Iyengar R N 1999 Earthquakes in ancient India; Curr. Sci. 77(6) 827–829.

Iyengar R N 2000 Seismic status of Delhi megacity; Curr. Sci. 78(5) 568–574.

Iyengar R N, Sharma D and Siddiqui J M 1999 Earthquake history of India in Medieval Times; Indian J. History Sci. 34(3) 181–237.

Jain K C 1972 Ancient cities & towns of Rajasthan: A study of culture and civilisation; Motilal Banarasi Dass, Delhi, 662p.

Jamteveit B, Petley-Ragan A, Incel S, Dunkel K G, Aupart C, Austrheim H, Corfu F, Menegon L and Renard F 2019 The effects of earthquakes and fluids on the metamorphism of the lower continental crust; J. Geophys. Res.: Solid Earth 124 7725–7755, https://doi.org/10.1029/2018JB016461.

Johnston A 1996 Seismic moment assessment of earthquakes in stable continental regions—I. Instrumental seismicity; Geophys. J. 124(2) 381–414, https://doi.org/10.1111/j.1365-246X.1996.tb05294.x.

Kothawale D R and Rajeevan M 2017 Monthly, seasonal and annual rainfall time series for All-India, homogeneous regions and meteorological subdivisions: 1871–2016, Research Report No. RR-138, Indian Institute of Tropical Meteorology. Pune. https://www.tropmet.res.in/~lip/Publication/RR-pdf/RR-138.pdf.

Li Q, Liu M and Stein S 2009 Spatiotemporal complexity of continental intraplate seismicity: Insights from geodynamic modeling and implications for seismic hazard estimation; Bull. Seismol. Soc. Amer. 99 52–60, https://doi.org/10.1785/0120080005.

Lilley F E M, Singh B P, Arora B R, Srivastava B J, Prasad S N and Sloane M N 1981 A magnetometer array study in northwest India; Phys. Earth Planet. Int. 25 232–240.

MacDonald A M, Bonsor H C, Ahmed K M, Burgess W G, Basharat M, Calow R C, Dixit A, Foster S S D, Gopal K, Lapworth D J, Lark R M, Moench M, Mukherjee A, Rao M S, Shamsudduha M, Smith L, Taylor R G, Tucker J, van Steenbergen F and Yadav S K 2016 Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations; Nature Geosci. 9 762–766.

Malik J N, Nakata T, Philip G, Suresh N and Virdi N S 2008 Active fault and palaeoseismic investigation: Evidence of a historic earthquake along Chandighar Fault in the Frontal Himalayan zone, NW India; Himal. Geol. 29(2) 109–117.

Mandal B, Sen M K, Vijaya Rao V and Mann J 2014 Deep seismic image enhancement with the common reflection surface (CRS) stack method: The Aravalli–Delhi Fold Belt of northwestern India: Geophys. J. Int. 196(2) 902–917, https://doi.org/10.1093/gji/ggt402.

Mandal B, Vaidya V R, Sen M K, Periyasamy K and Sarkar D 2018 Common reflection surface stack imaging of the Proterozoic Chambal Valley Vindhyan basin and its boundary fault in the northwest India: Constraints on crustal evolution and basin formation; Tectonics 37 1393–1410, https://doi.org/10.1002/2017TC004895.

Miller S A, Colletti C, Chiaraluce L, Cocco M, Barchi M and Kaas B J P 2004 Aftershocks driven by a high-pressure CO2 source at depths; Nature 427(6976) 724–727.

Mishra D C and Ravi Kumar M 2014 Proterozoic orogenic belts and rifting of Indian cratons: Geophysical constraints; Geosci. Frontiers 5 25–41.

Mishra V, Asoka A, Vatta K and Lall U 2018 Groundwater depletion and associated CO2 emissions in India; Earth’s Future 6(12) 1672–1681, https://doi.org/10.1029/2018EF000939.

Mondal M E A 2003 Are the Bundelkhand craton and the Banded Gneissic Complex parts of one large Archaean protocontinent? evidence from ion microprobe 207Pb/206Pb data on c dykes, zircon zircons; Geosci. Frontiers 5 25–41.

Naqvi S M and Rogers J J W 1987 Precambrian Geology of India; Oxford University Press, New York, 223p.

Narula P L, Shome S K and Murthy B S R (eds) 1996 Killari Earthquake 30 September 1993; Geol. Surv. India, Spec. Publ. 37, Government of India.

Nath M, Narain K and Srivastava J P 1968 The Delhi earthquake of 27th August, 1960; Rec. Geol. Surv. India 98 367–382.

Oldham T 1883 A catalogue of Indian earthquakes from the earliest time to the end of AD 1869; Geol. Surv. India Memoir 29 163–215.

Philip G, Suresh N and Bhakuni S S 2014 Active tectonics in the northwestern outer Himalaya: Evidence of large-magnitude palaeoearthquakes in Pinjaur Dun and the Frontal Himalaya; Curr. Sci. 106(2) 211–222.
Rao M R 1973 The subsurface geology of the Indo-Gangetic plains; J. Geol. Soc. India 14 217–242.
Richardson R M, Solomon S C and Sleep N H 1979 Tectonic stress in the plates; Rev. Geophys. 17 981–1019. https://doi.org/10.1029/RG017i005p00981.
Rodell M, Velicogna I and Famiglietti J S 2009 Satellite-based estimates of groundwater depletion in India; Nature 460(7258) 999–1002.
Sastri V V, Bhandari L L, Raju A T R and Dattha A K 1971 Tectonics framework and subsurface stratigraphy of the Ganga basin; J. Geol. Soc. India 12 232–233.
Sharma R S 1988 Patterns of metamorphism in the Precambrian rocks of the Aravalli Mountain belt; In: Precambrian of the Aravalli Mountain, Rajasthan, India (ed.) Roy A B, Geol. Soc. India Memoir 7 33–75.
Sharma R S 2009 Cratons and Fold Belts of India; Springer-Verlag Berlin, Heidelberg, 304p.
Sharma, V, Wadhawan M, Rana N, Sreejith K M, Agrawal R, Kamra C, Hosilakar K S, Narkhede K V, Suresh G and Galahaut V K 2020 A long duration non-volcanic earthquake sequence in the stable continental region of India: The Palghar swarm; Tectonophysics. 779 228376, https://doi.org/10.1016/j.tecto.2020.228376.
Shukla A K, Prakash R, Singh R K, Mishra P S and Bhatnagar A K 2007 Seismotectonic implications of Delhi region through fault plane solutions of some recent earthquakes; Curr. Sci. 93 1848–1853.
Silson R H 1996 Structural permeability of fluid-driven fault–fracture meshes; J. Struct. Geol. 18 1031–1042.
Singh S K, Kumar A, Suresh G, Ordaz M, Pacheco J F, Sharma M L, Bansal B K, Datarayam R S and Reinoso E 2010 Delhi earthquake of 25 November 2007 (Mw 4.1): Implications for seismic hazard; Curr. Sci. 99(7) 939–947.
Singh S K, Suresh G, Dattatrayam R S, Shukla H P, Martin S, Havskov J and Igelias A 2013 The Delhi 1960 earthquake: Epicenter, depth and magnitude; Curr. Sci. 105(8) 1155–1165.
Sinha-Roy S 1988 Proterozoic Wilson cycles in Rajasthan; In: Precambrian of the Aravalli Mountain, Rajasthan, India (ed.) Roy A B, Geol. Soc. India Memoir 7 95–108.
Sloan R A, Jackson J A, McKenzie D and Priestley K 2011 Earthquake depth distributions in central Asia, and their relations with lithospheric thickness, shortening and extension; Geophys. J. Int. 185 1–29, https://doi.org/10.1111/j.1365-246X.2010.04882.x.
Srivastava A K and Jalote P M 1977 Seismicity and tectonic set up of the area around Delhi; Proc. Sixth World Conference on Earthquake Engineering, New Delhi 1 791–798.
Srivastava H N and Ramachandran K 1985 New catalogue of earthquakes for Peninsula India during 1839–1900; Mausam 35(3) 351–358.
Srivastava S K, Prakash R, Dattatrayam R S, Arora S K and Bansal B K 2005 Configuration of an optimum seismic network for India; Mausam 56(2) 465–472.
Steen S, Liu M, Calais E and Li Q 2009 Mid-Continent earthquakes as a complex system; Seismol. Res. Lett. 80(4) 551–553.
Stevens V L and Avouac J-P 2015 Interseismic coupling on the main Himalayan thrust; Geophys. Res. Lett. 42 5828–5837, https://doi.org/10.1002/2015GL064845.
Sugden T J, Deb M and Windley B F 1990 The tectonic setting of mineralisation in Proterozoic Aravalli Delhi orogenic belt, NW India; In: Precambrian continental crust and its economic resources (ed.) Naqvi S M , Dev. Precamb. Geol. 8 367–390.
Sychanthavong S P H and Desai S D 1977 Protoplate tectonics controlling the Precambrian deformations and metallogenic epochs of NW Peninsular India; Mineral. Sci. Eng. 9 218–237.
Szeliga W, Hough S E, Martin S and Bilham R 2010 Intensity, magnitude, location and attenuation in India for felt earthquakes since 1762; Bull. Seismol. Soc. Am. 100(2) 570–584.
Tandon A N 1975 Some typical earthquakes of north and west Uttar Pradesh; Bull. Indian Soc. Earthq. Technol. 12(4) 74–88.
Tandon A N and Srivastava H N 1974 Earthquake occurrence in India; In: Earthquake Engineering (Jai Krishna Volume), Indian Society of Earthquake Technology, pp. 1–44.
Tiwari D K, Jha B, Kundu B, Galahaut V K and Vissa N K 2021 Groundwater extraction-induced seismicity around Delhi region, India; Scientific Reports 11(1) 1–14.
Tiwari V M, Wahr J and Svenson S 2009 Dwindling groundwater resources in northern India, from satellite gravity observations; Geophys. Res. Lett. 36 L18401.
Valdiya K S 1976 Himalayan transverse faults and folds and their parallelism with subsurface structures of north Indian planes; Tectonophysics. 32 353–386.
Vavryčuk V 2014 Iterative joint inversion for stress and fault orientations from focal mechanisms; Geophys. J. Int. 199(1) 69–77, https://doi.org/10.1093/gji/ggu224.
Verma P K and Greiling R O 1995 Tectonic evolution of the Aravalli orogen (NW India): An inverted Proterozoic rift basin?; Geologische Rundschau 84 683–696.
Vijaya Rao V, Prasad B R, Reddy P R and Tewari H C 2000 Evolution of Proterozoic Aravalli Delhi fold belt in the northwestern Indian shield from seismic studies; Tectonophysics. 327(1–2) 109–130, https://doi.org/10.1016/S0040-1951(00)00156-6.
Walker 1907 Groundwater disturbances; Mon. Wea. Rev. 92–93.
Wessel P and Smith W H 1991 Free software helps map and display data; Eos, Trans. Am. Geophys. Union 72(41) 441–446.
Wolin E, Stein S, Pazzaglia F, Meltzer A, Kafka A and Berti C 2012 Mineral, Virginia, earthquake illustrates seismicity of a passive-aggressive margin; Geophys. Res. Lett. 39 L02305, https://doi.org/10.1029/2011GL050310.
Wu P and Johnston P 2000 Can deglaciation trigger earthquakes in North America?; Geophys. Res. Lett. 27(9) 1323–1326.
Yadav R K, Galahaut V K, Kumar A, Sati S P, Catherine J, Gautam P, Kumar K and Rana N 2019 Strong seismic coupling underneath Garhwal–Kumaun region, NW Himalaya, India; Earth Planet. Sci. Lett. 506 8–14, https://doi.org/10.1016/j.epsl.2018.10.023.