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# Recurrent seismicity in Rajasthan State in the tectonically stable NW Indian Craton

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## Abstract

Indian peninsular region comprises several Archean cratonic blocks (Dharwar, Bastar, Singhbhum, Aravalli – Bundelkhand), bordered by Proterozoic mobile belts. Therefore, this region is considered as tectonically stable and designated as the least vulnerable region to earthquake hazard except the still active Central Indian Tectonic Zone (CITZ). The latter is a major suture between southern and northern Indian blocks. Seismicity in India is common along its northern and northeastern (Himalayan) region defining the Indian Plate margin, in collision with the Eurasian (Tibetan) Plate. Being tectonically active, this region has a documented record of frequent earthquakes including some high magnitude and devastating ones. The northwestern Indian block is amongst the relatively stable Precambrian regions of India and categorized under Zone – II by the Indian Meteorology Department, one of the seismically least vulnerable regions. However, the region has been a site of recurring low to moderate magnitude earthquakes. Compilation of the earthquake data from the Rajasthan State in NW India documents at least 45 earthquakes in this region during the last one and a half decades. Several of these have remained unnoticed because of their low magnitude. The NE –SW trending Aravalli Mountain Region (AMR), running across the eastern half of Rajasthan State represents the most significant tectonomorphic feature of NW India. The AMR is an ensemble of Proterozoic age Aravalli and Delhi Supergroup rocks (metasediments, volcanics and intrusives) that overlie an Archean basement (Banded Gneissic Complex – BGC). These Proterozoic mobile belts have evolved through several episodes of deformation that have shaped its present day geomorphology. The western part of the State, the Marwar Block, is relatively younger in age and was accreted to the AMR during the 1 Ga subduction event. The western margin of AMR, also called as the Western Margin Fault, represents a major suture between the two terranes. However, the entire region was cratonized by end Proterozoic and has remained tectonically stable during the Phanerozoic Eon. The Archean basement and overlying Proterozoic cover rocks are infested with several major and minor faults and shear zones. The most prominent ones are the NE-SW trending major lineaments corresponding with the regional tectonic grain and several minor ones across. The earthquake epicenter distribution pattern shows a close spatial association with these lineaments. In the absence of any significant tectonic activity in the region and rise in pore pressure either due to magmatism or excessive rainfall, we attribute recurrence of earthquakes in the region to reactivation of such old sutures/weaker zones as a response to stress build-up along the northern margin of the Indian Plate resulting from ongoing northward convergence of the Indian Plate. Some of the faults in western part are traceable into the Cambay Basin active faults in the south that may have triggered seismic activity in western Rajasthan.

***Keywords:*** *Recurrent Seismicity, Lineaments, Reactivation, NW India, Rajasthan, Indian Plate Convergence*

## 1. Introduction

Seismicity hazard is an issue of serious concern because of the magnitude of destruction the earthquakes may cause. It is one of the most disastrous natural hazards that cannot be controlled or averted but an indepth geological understanding would help in identification and demarcation of earthquake vulnerable regions for better preparedness to minimize the loss of life. In the Indian context, the poor construction and inappropriate building design also contribute significantly toward loss of life and property. Earthquake hypocentres may be shallow to deep, depending upon ongoing tectonic activity in the lower crust – upper mantle region. Therefore, earthquakes are typically associated with the tectonically active regions in the present day scenario, such as the active plate margins and within plate rift zones.

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The Circum Pacific Belt (Ring of Fire), Mediterranean Alpine – Himalayan region, the Mid Atlantic Ocean region, can be named as the most prominent seismic zones/belts. Besides, several other regions experience frequent earthquakes of sizable magnitude. The old (Archean – Proterozoic) terrains that have cratonized more than 500 million years ago and do not have any tectonic history during the Phanerozoic, are considered tectonically stable and seismically safe. However, instances of occasional low to moderate magnitude earthquakes are not uncommon even in the most stable shield areas (Kayal, 2008). Roy (2006), has questioned the 'seismically stable' status of the Indian Peninsular region (Indian Shield), based on apparent differences with other shield regions i.e., the Canadian Shield. The Indian Shield lies close to the active Himalayan belt and a considerable part of it forms part of the Himalayan edifice. There are records of high magnitude earthquakes (>8 magnitude) in this region that are usually associated with collision tectonics (Roy 2006). Besides, the unusually high heat-flow over parts of the Peninsular Indian Shield indicates an abnormally hot crust, unlike the heat-flow pattern in other shield areas of the world (Rao et al. 1976; Singh 1985). The Bouguer gravity anomaly maps published by the National Geophysical Research Institute, Hyderabad show high positive values (>40 mGal) in several parts of India, which according to Negi et al. (1986) indicate 'mobility' rather than stability.

The northwestern Indian terrain is one such 'stable' region that largely comprises an Archean – Proterozoic crystalline basement and overlying fold belts with a record of multiple episodes of metamorphism and deformation during the Precambrian (Sinha-Roy et al. 1995, 1998; Gupta et al. 1997; Roy and Jakhar 2002, and references therein). The region west of the Aravalli Mountain Belt, is a geologically younger domain, known as the Marwar Block (de Wall et al. 2012). The oldest rocks known from this western segment are the ~830 Ma trondhjemitic gneisses (Pradhan et al. 2010), overlain and intruded by the 780 – 750 Ma volcano-plutonic rocks of the Malani Igneous Suite (Gregory et al. 2009; Wang et al. 2017; Zhao et al. 2018). These together form the basement for the overlying Precambrian – Cambrian Marwar Supergroup and Mesozoic – Tertiary sedimentats (Pandit et al. 2001, Roy and Jakhar 2002; Pandey and Bahadur 2009). The northwestern India has been largely demarcated as Zone II (relatively least seismically hazardous zone) in the seismic zonation (earthquake hazard) map of India, published by the Indian Meteorology Department. Therefore, it is intriguing to note frequent occurrence (two or more per year) of low to moderate magnitude earthquakes in the State of Rajasthan in NW India, which is a cratonized terrain with no major known tectonic activity since Late Proterozoic volcano-plutonic magmatism of Malani Igneous Suite. We have documented and inventoried earthquake occurrences in Rajasthan State in NW India during the recent years and have evaluated them vis-à-vis regional tectonic fabric. Spatial distribution of earthquake epicenters with fossil-sutures and fault zones has been evaluated for their possible reactivation due to stress build-up related to northward drift and collision of the Indian Plate.

## 2. Geological and geomorphological overview

Rajasthan State can be subdivided into several physiographic domains, evolved through sustained degradational and aggradational processes during Late Tertiary and Quateranry periods (Sinha-Roy et al. 1998). The most prominent physiographic feature of the region is the NE – SW trending Aravalli Mountain that traverses the eastern part of the State from Delhi in the north into the northern part of the adjoining Gujarat State in the south. The Aravalli Hills or Aravalli Mountain Region also hosts the oldest rocks of the region. The region to the west of Aravalli Orographic Axis is known as the Western Plains that comprises a largely peneplained alluvial sandy tract. The westernmost part of the State is the Thar Desert that forms the eastern limit of the vast Saharan arid tract (Sinha-Roy et al. 1998). The volcanic and plutonic rocks of Malani Igneous Suite and some hills comprising Phanerozoic sediments rise above the western sandy plains as isolated outcrops. The region to the east of Aravalli Mountain Region, is known as the eastern plains and comprises parts of the fertile Gangetic plains and sedimentary (Vindhyan Supergroup) hills.

In the geological context the oldest group of rocks is the ~3.3 – 2.5 Ga, Banded Gneiss Complex (Heron 1953; Roy and Jakhar 2002) that can be traced further east into the Bundelkhand Craton in north-central India (Meert et al. 2010). The highly deformed and migmatized granite gneisses, mafic and acid intrusive rocks of the Banded Gneiss Complex (BGC) form the basement for two overlying supracrutal sequences, namely Aravalli (Paleoproterozoic) and Meso- Neoproterozoic, Delhi supergroups (Heron 1953). Both the basement and cover rocks have undergone multiple episodes of deformation, metamorphism and magmatism (Sinha-Roy et al. 1998; Roy and Jakhar 2002; Meert and Pandit 2015 and references therein). All the major tectonic features in the region show a prominent NE – SW alignment that also marks the strongest regional tectonic grain (Gupta et al. 1997). A general younging towards west can be seen and the region west of the Aravalli Mountain Region (Aravalli – Delhi Fold Belt) is named as the Marwar Block (accreted to the Indian Block during 1 Ga convergence; see de Wall et al. 2012, Bhowmik et al. 2012). Vast areas of Marwar Block comprise volcano-plutonic rocks of 780 – 750 Ma Malani Igneous Suite (Bhushan and Chandrasekharan 2002, Gregory et al. 2009; Zhao et al. 2018). Rocks of the Malani Igneous Suite form the basement for the Ediacaran – Cambrian sediments of Marwar Supergroup (Pareek 1984; Pandit et al. 2001; Pandey and Bahadur 2009). Phanerozoic sediments of Mesozoic and Tertiary age are exposed further west while a large area is occupied by the Quaternary sands of the Thar Desert (Sinha-Roy et al. 1998; Roy and Jakhar 2002). The boundary between Aravalli Delhi Fold Belt and Marwar Block is a major tectonic feature, known as the Western Margin Fault (Gupta et al. 1997). It is marked by linear occurrence of mafic – ultramafic rocks that are collectively described as the Phulad Ophiolite Suite (Sinha-Roy et al. 1998). The eastern limit of Aravalli – Delhi Fold Belt is also a major tectonic feature, known as the Great Boundary Fault that juxtaposes the sediments of Vindhyan Supergroup and older rocks of AMR. Most of the stratigraphic boundaries are tectonized and define major NE – SW trending lineaments. The lineament distribution and geometry is discussed in more detail in the following section.

## 3. Lineament distribution in Rajasthan

Bakliwal and Ramasami (1987) documented all the major lineamnets in Rajasthan State and their disposition and alignments is presented in Fig 1. The diagram shows an intricate network of lineaments that are surface expression of old faults developed during several episodes of deformation. The 'Seismotectonic Atlas' of India (Dasgupta et al. 2000) subdivides the Rajasthan lineaments into two groups, (i) those formed as new features cross cutting all the rock formations and (ii) ones developed as reactivated Precambrian grains (Roy 2006). Major fold belts, lineaments and faults of Rajasthan State are listed below (Bakliwal and Ramasami 1987; Dasgupta et al. 2000; Figs. 1, 2).

1. Aravalli Fold Belt
2. Delhi Fold Belt
3. Jaisalmer-Barwani Lineament
4. Rajkot-Lathi Lineament
5. West Coast Lineament
6. Luni-Sukri Lineament
7. Rakhabdev Lineament
8. Pisangan-Vadnagar Lineament
9. Kishangarh Chippri Lineament
10. Chambal Jamnagar Lineament
11. Ajmer-Sandia Lineament
12. Delwara Lineament
13. Tonk Lineament
14. Chittaugarh Machilpur Lineament/ Great Boundary Fault
15. Mehanda-Stepped Graben
16. Jaipur Depression Jaipur Uplift

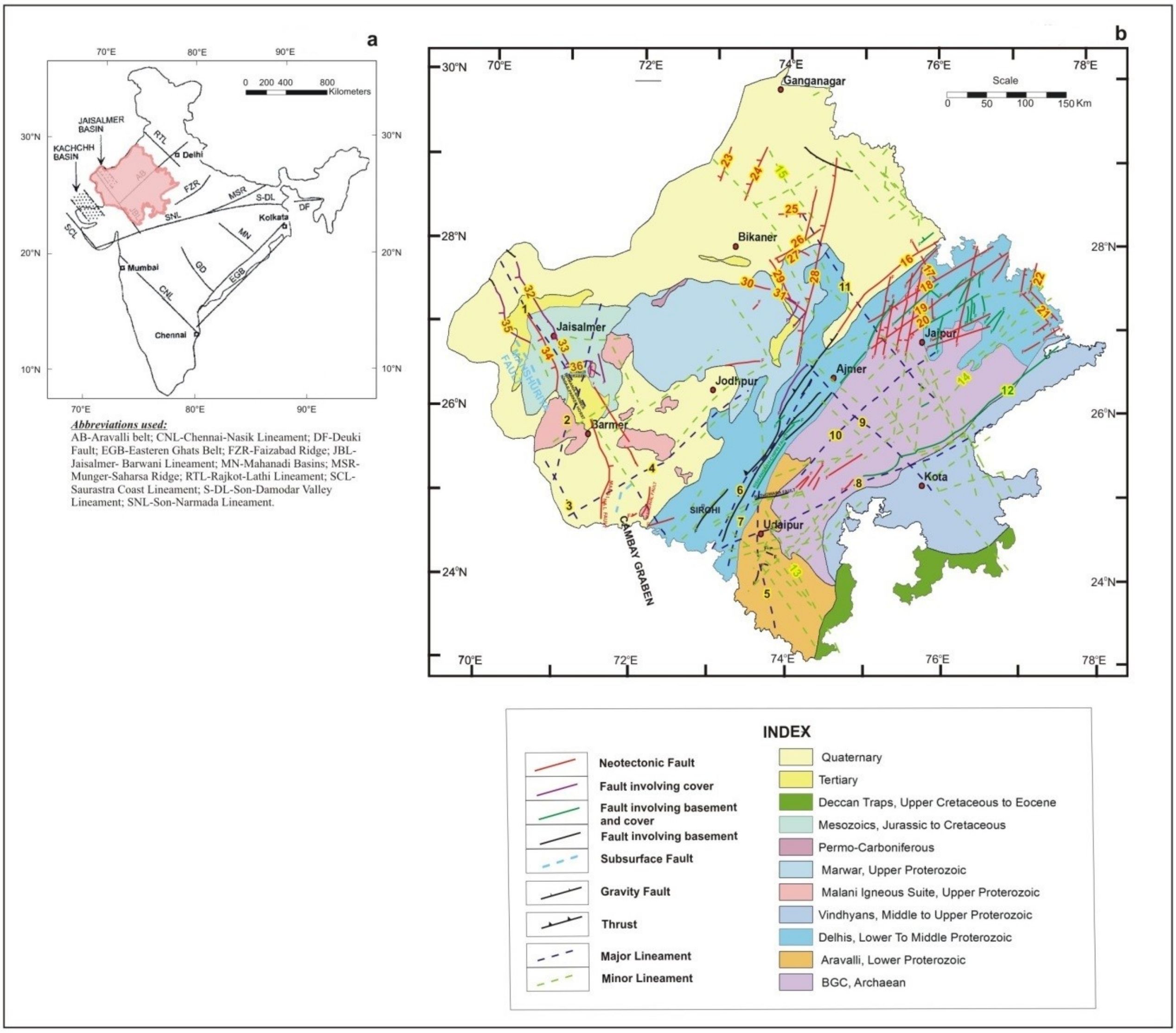


Fig 1. (a) Map of India showing Major Tectonic Lineaments (after Roy 2004) and Location of the Study area (shown in pink). (b) Map of Rajasthan Showing an overlay of Geology, Lineaments and Faults. Compiled from Seismotectonic Atlas of India and its Environs (Dasgupta et al. 2000) and Geological Map of Rajasthan (GSI). For Lineament and Fault nomenclature please refer to Fig 2.

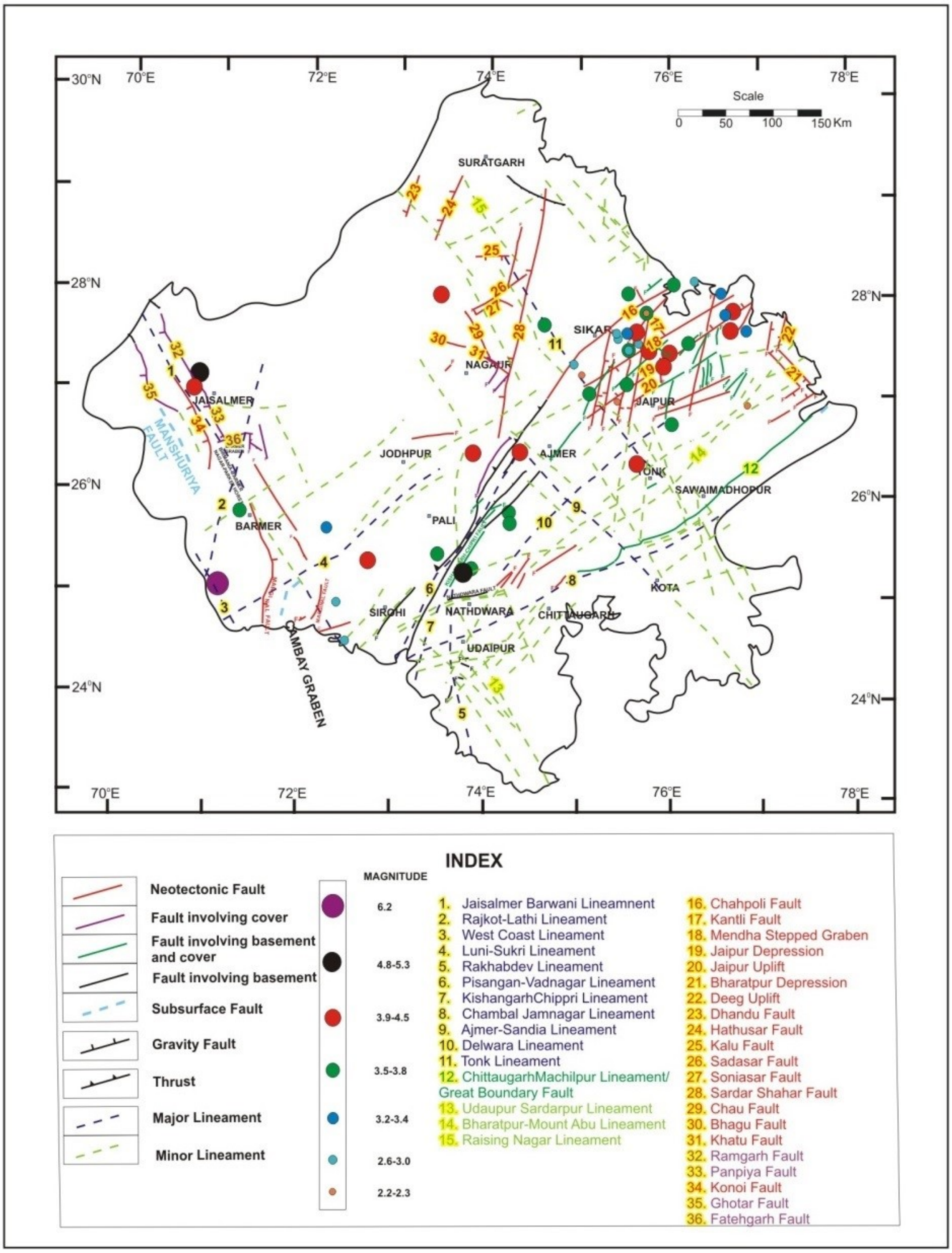


Fig 2. Map of Rajasthan showing an overlay of Lineaments, Faults and Earthquake occurrences during last 15 years. Compiled from Seismotectonic Atlas of India and its Environs (Dasgupta et al. 2000).

As seen in Fig 1, the lineament density is maximum in the eastern part of the State, i.e. in the Aravalli Mountain Region or the Aravalli – Delhi Fold Belt. Prominent lineaments in this region are; Chambal Jamnagar Lineament, Pisangan-Vadnagar Lineament, Delwara Lineament, Ajmer-Sandia Lineament, Rakhabdev Lineament, Kishangarh Chippri Lineament, Tonk Lineament, Chittaurgarh Machilpur Lineament/ Great Boundary Fault and Raysing Nagar - Tonk Lineament. A number of large scale faults in the Delhi Supergroup rocks in the region north of Jaipur have been mapped by Das (1988) who named them as Jaipur Depression, Jaipur Uplift, Mendha Stepped Graben, Chahpoli Fault and Kantli Fault. These faults, defining a NW-SE and NE-SW conjugate disposition, effected rotation and tilting of rock units and considerable strike slip displacements (Roy and Jakhar 2002). Relatively smaller number of lineaments and faults are present in the western part of the state, the prominent ones being Luni-Sukri Lineament, Jaisalmer-Barwani Lineament, Rajkot-Lathi Lineament and West Coast Lineament. The Jaisalmer-Barwani Lineament marks the western boundary of the Mesozoic-Cenozoic Basin in the Barmer area and the boundary between Barmer Graben in the east and Birmania - Barmer - Nagar Parkar Horst in the west.

Majority of lineaments have rectilinear disposition, irrespective of their antiquity and geomorphology of the terrain. Such orientation in high relief terrains suggests steep to subvertical dips for these tectonic features. Majority of lineaments and faults trend ENE-WSW, corresponding with the prominent tectonic grain of the Aravalli – Delhi Fold Belt. Relatively less prominent NNW-SSE trend can be correlated with tectonics in the Dharwar region in south India. The latter trends are observed not only in Rajasthan but also in the entire Peninsular India (Roy 2006). Some N-S trending lineaments have also been demarcated in Rajasthan.

## 4. Earthquake occurrences in Rajasthan

### 4.1. Major earthquakes

Rajasthan State has been broadly classified as Zone – II in the Seismic Zonation (hazard) Map of India, published by the Indian Meteorology Department, indicating a seismically least vulnerable region. This is similar to other cratonized blocks of southern and east-central India. However, low magnitude earthquakes commonly occur in this region, occasionally with more than three magnitude (Table 1, 2). Some of the recent earthquake occurrences during last decade and a half are listed in Table 2.

### 4.2. The more recent earthquake events

Compilation of earthquake data (sourced from the Indian Meteorological Department repository) underlines about 45 earthquakes of magnitude 2.2 to 5.3 (Table 2). Of these, six earthquakes occurred in 2016 alone, the highest number in a single year. Recurrence of earthquakes, albeit low magnitude ones, is clearly documented by the data. The table also lists the 1906 earthquake, which is the strongest one recorded so far in this region.

Location of the earthquake epicenters has been superimposed onto the lineament map of Rajasthan in Fig 2. As evident from the figure, majority of the earthquake occurrences are confined to the eastern part of the State and show a close spatial association with dense network of lineaments in the region. The largest earthquake of the State so far, the magnitude 6 Thar Desert Earthquake (1906) shows a close spatial association with the West Coast Lineament that runs along the southwestern extremity of Rajasthan State. The 5.3 magnitude Jaisalmer Earthquake of April, 2009 can be regarded as the strongest earthquake among the more recent ones. Details provided in table 2, underline recurrence of seismicity in this, otherwise tectonically stable, region.

## 5. Discussion on Spatial distribution of earthquake and tectonic features

The location of earthquake epicenters was superimposed onto the lineament map of Rajasthan to evaluate their possible association with faults and other tectonic features (Fig. 2). Incidentally, the highest concentration of earthquake epicenters is seen in the NE segment, the North Delhi Fold Belt terrane (Sinha-Roy 1984; Wang et al. 2017). The earthquake epicenter distribution pattern underlines a distinct spatial association with faults/lineaments.

Table 1. Important earthquake occurrences in Rajasthan in the recent past (data source: Indian Meteorology Department) and spatially associated lineament / fault

| Sr. No. | Location of Earthquake | Magnitude and Intensity | Associated fault/lineament |
|---|---|---|---|
| 1 | Churu (1974) | Magnitude –3.5<br>Intensity – IV | SardarShahar Fault |
| 2 | Pali (1979) | Magnitude – 3.4<br>Intensity – II & III | Phulad Lineament |
| 3 | Jaisalmer (1991) | Magnitude – 6.3<br>Intensity – VII+ | Kanoi Fault |
| 4 | Udaipur (1996) | Magnitude – 4.3<br>Intensity - +V | Intersection of Chipri and Bharatpur -Mt. Abu lineaments. |
| 5 | Sirohi | Magnitude – 4.9 | Phulad Lineament. |
| 6 | Jaipur | Magnitude – 4.5 | Mendha seeped Graben or Jaipur Depression of Das (1988). |

Table 2. Details of more recent earthquake events in Rajasthan (Source: Indian Meteorological Department http://www.imd.gov.in/pages/earthquake_prelim.php and other sources)

| S.N. | DATE | TIME HRS (IST) | LAT (deg.N) | LONG (deg.E) | Depth (km) | Magnitude | Region |
|---|---|---|---|---|---|---|---|
| 1 | 15/08/1906 | 22:11 | 25.0N | 71.0 | | 6.2 | THAR DESERT, RAJASTHAN |
| 2 | 10/08/2003 | 11:17:55 | 27.38N | 75.98 | 10.0 | 4.4 | SHAHPURA –JAIPUR REGION, RAJASTHAN |
| 3 | 19/02/2004 | 2:40:49 | 25.3N | 72.66 | 7.9 | 4.1 | JALORE, RAJASTHAN |
| 4 | 29/11/2006 | 05:41:14.2 | 27.6°N | 76.7°E | 13.0 | 3.9 | ALWAR,RAJASTHAN |
| 5 | 23/12/2006 | 22:43:26.6 | 26.7N | 76.0E | 10 | 3.7 | JAIPUR,RAJASTHAN |
| 6 | 16/03/2007 | 4:46:25.3 | 27.6°N | 76.9°E | 10.0 | 3.3 | ALWAR, RAJASTHAN |
| 7 | 15/09/2007 | 8:57:45.1 | 27.5°N | 75.4°E | 27.9 | 2.8 | SIKAR, RAJASTHAN |
| 8 | 20/11/2007 | 17:11:5.6 | 28.0°N | 76.6°E | 01.2 | 3.3 | RAJASTHAN--HARYANA BORDER |
| 9 | 27/06/2008 | 7:53:38.7 | 25.2°N | 73.8°E | 05.0 | 3.6 | RAJ SAMAND, RAJASTHAN |
| 10 | 05/07/2008 | 11:59:37.6 | 25.8°N | 74.2°E | 10.0 | 3.6 | BHILWARA, RAJASTHAN |
| 11 | 28/12/2008 | 07:39:52 | 25.6 N | 72.2 E | 15 | 3.2 | BARMER, RAJASTHAN |
| 12 | 08/02/2009 | 15:42:13 | 27.4°N | 75.5°E | 5 | 2.8 | RAJASTHAN |
| 13 | 09/04/2009 | 01:46:57.0 | 27.1°N | 70.7°E | 33 | 5.3 | JAISALMER, RAJASTHAN |
| 14 | 29/10/2009 | 14:05:49 | 26.9°N | 76.9°E | 5 | 2.3 | JAIPUR, RAJASTHAN |
| 15 | 12/01/2010 | 05:46 | 26.9°N | 75.4°E | | 2.3 | JAIPUR, RAJASTHAN |
| 16 | 07/04/2010 | 07:05:51 | 27.8°N | 76.6°E | 22 | 3.3 | DISTT. ALWAR, RAJASTHAN |
| 17 | 28/05/2010 | 10:15:49 | 27.8°N | 75.7°E | 28 | 2.2 | DISTT. SIKAR, RAJASTHAN |
| 18 | 15/08/2010 | 06:08:52 | 26.4°N | 74.3°E | 10 | 4.0 | AJMER, RAJASTHAN |
| 19 | 09/11/2010 | 22:46:19 | 25.2°N | 73.7°E | 4 | 4.8 | DISTT. RAJSAMAND, RAJASTHAN |
| 20 | 26/02/2011 | 15:40:08 | 27.5°N | 75.6°E | 10 | 3.0 | NIM KA THANA, (DISTT SIKAR), RAJASTHAN |
| 21 | 12/10/2011 | 10:27:25 | 28.2°N | 76.0°E | 6 | 3.5 | RAJASTHAN (JHUNJHUNUN DIST) - HARYANA (MAHENDRAGARH DIST) BORDER REGION |
| 22 | 30/10//2012 | 17:21:51 | 25.8°N | 71.2°E | 10 | 3.5 | BARMER, RAJASTHAN |
| 23 | 20/12/2012 | 13:00:56 | 27.5°N | 76.2°E | 5 | 3.6 | KOTHPUTLI, RAJASTHAN |
| 24 | 24/02/2013 | 00:57:17 | 26.3°N | 75.6°E | 5 | 4.1 | TONK, RAJASTHAN |
| 25 | 31/03/2013 | 14:43:21 | 27.2°N | 75.0°E | 5 | 2.3 | NEAR SAMBHAR LAKE, RAJASTHAN |
| 26 | 05/08/2013 | 07:27:06 | 27.0°N | 70.7°E | 20 | 4.0 | JAISALMER, RAJASTHAN |
| 27 | 27/04/2014 | 09:14:04 | 27.6°N | 75.5°E | 5 | 3.4 | SIKAR, RAJASTHAN |
| 28 | 19/11/2014 | 15:26:00 | 24.5°N | 72.4°E | 5 | 2.9 | SIROHI, RAJASTHAN |
| 29 | 03/09/2015 | 23:27:50 | 27.6°N | 75.6°E | 10 | 4.4 | SIKAR, RAJASTHAN |
| 30 | 28/01/2016 | 04:17:08 | 27.1°N | 75.5°E | 10 | 3.8 | JAIPUR, RAJASTHAN |
| 31 | 24/02/2016 | 07:36:51 | 24.9°N | 72.3°E | 26 | 3.0 | JALORE, RAJASTHAN |
| 32 | 18/03/2016 | 09:07:33 | 25.4°N | 73.4°E | 33 | 3.5 | PALI, RAJASTHAN |
| 33 | 08/04/2016 | 01:33:19 | 27.0°N | 75.1°E | 15 | 3.5 | NAGAUR, RAJASTHAN |
| 34 | 17/11/2016 | 04:28:56 | 27.8°N | 76.7°E | 10 | 4.4 | RAJASTHAN HARYANA BORDER REGION |
| 35 | 26/12/2016 | 21:47:18 | 25.7°N | 74.2°E | 10 | 3.5 | RAJSAMAND-BHLWARA, RAJASTHAN |
| 36 | 17/03/2017 | 15:54:17 | 28.1°N | 76.3°E | 5 | 2.6 | RAJASTHAN HARYANA BORDER REGION |
| 37 | 24/03/2017 | 12:42:25 | 27.6°N | 75.4°E | 5 | 2.9 | SIKAR, RAJASTHAN |
| 38 | 18/11/2017 | 15:21:19 | 26.4°N | 73.8°E | 10 | 4.2 | JODHPUR, RAJASTHAN |
| 39 | 08/07/2018 | 09:43:22 | 27.3°N | 75.9°E | 10 | 4.3 | DISTRICT JAIPUR, RAJASTHAN |
| 40 | 24/08/2018 | 03:25:50 | 27.8°N | 75.7°E | 18 | 3.7 | DISTT. JHUNJHUNU, RAJASTHAN |
| 41 | 30/08/2018 | 23:34:36 | 27.5°N | 75.6°E | 05 | 3.5 | DISTRICT-SIKAR,RAJASTHAN |
| 42 | 17/03/2019 | 05:11:29 | 27.4°N | 75.7°E | 10 | 4.0 | DISTT.- SIKAR, RAJASTHAN |
| 43 | 03/05/2019 | 10:51:51 | 27.3°N | 74.9°E | 10 | 3.0 | DISTT. NAGAUR, RAJASTHAN |
| 44 | 03/07/2019 | 20:59:25 | 27.6°N | 74.6°E | 35 | 3.5 | DISTT. NAGAUR, RAJASTHAN |
| 45 | 04/09/2019 | 15:30:30 | 28.0°N | 75.5°E | 16 | 3.8 | DISTT. JHUNJHUNU, RAJASTHAN |
| 46 | 13/10/2019 | 10:36:34 | 28.0°N | 73.4°E | 10 | 4.5 | DISTT. BIKANER, RAJASTHAN |

The Aravalli – Delhi Fold Belt region in the eastern part of the State was cratonized by end Proterozoic with no further tectonic activity, therefore, recurrence of earthquakes in this region is rather intriguing. In the absence of any known tectonic activity in the region we relate earthquake occurrence to reactivation of the old faults. The Shahpura-Jaipur Earthquake of August 2003 and Jaipur Earthquake of December 2006 (magnitude 3.7) can be associated with the Jaipur Depression and Delwara Lineament (NE-SW trending), respectively, in the northern part of the State. The Rajasthan-Haryana Border Earthquake of November 2007 (magnitude 3.3) at the northeastern extremity can be associated with the NE-SW trending Mendha Stepped Graben. Jaipur

Earthquake of October 2009 (magnitude 2.3) can be associated with the Bharatpur-Mt. Abu Lineament. The Jaipur Earthquake of January 12, 2010 (magnitude 2.3) can be linked with the Jaipur Depression. The Alwar Earthquake of April 7, 2010 (magnitude 3.3), Kotputali Earthquake of December 20, 2012 (magnitude 3.6) and Rajasthan-Haryana Earthquake of November 17, 2016 (magnitude 4.4) also show association with the Jaipur Depression. The Sikar Earthquake (magnitude 2.2) of May 28, 2010 is associated with NW-SE trending Kantli Fault. The Ajmer Earthquake of August 15, 2010 (magnitude 4.0) seems related to the intersection of NE-SW trending Pisangan Vadhnagar Lineament and NW-SE trending Ajmer Sandia Lineament. The 4.8 magnitude, November 2010 Rajsamand Earthquake (highest magnitude among the recent ones in AMR) can be associated with the Kishangarh Chippari Fault. The Neem Ka Thana Earthquake of February 26, 2011 (magnitude 3.0) can be associated with N-S trending fault system and the Rajasthan - Haryana Border Earthquake (magnitude 3.5) of October 2011 with the NE-SW trending Chapoli Fault. The Tonk Earthquake (magnitude 4.1) of February 2013, Sambhar Lake Earthquake of 2.3 magnitude of March 31, 2013 and Nagaur Earthquake of April 2016 (magnitude 3.5) can be associated with the Tonk Lineament.

As shown in Fig 1 (*see also* Tab. 2), earthquakes of 3.6 magnitude that occurred in Rajsamand on June 27, 2008 and Bhilwara on July 05, 2008, can be associated with a prominent thrust zone, the Kaliguman Dislocation Zone which also marks the boundary between South Delhi Fold Belt and Sandmata - Mangalwar Complex. The Shahpura-Jaipur Earthquake of August 2003 (magnitude 4.4) and Alwar Earthquake of November 2006 (magnitude 3.9) can be associated with (tectonized) the contact zone between Alwar and Ajabgarh groups of Delhi Supergroup. The March 2017, Rajasthan - Haryana border earthquake can also be associated with this zone.

The above discussion provides clear evidence of close spatial association of the recent earthquakes with some old fault/lineaments. The Western Margin Fault, a prominent (1 Ga) suture between Aravalli Craton in the east and Marwar Block in the west, is the locale for several earthquakes. The earthquake occurrence in the Rajasthan State can be attributed to reactivation of the old weak planes/zones. Since the region does not have any history of Phanerozoic tectonism, the trigger for reactivation needs to be identified. Northward drift and continued collision of the Indian Plate with the Eurasian Plate causes stress build up, resulting in frequent earthquakes along the tectonically active, northern margin of the Indian Plate, the highest earthquake vulnerability zone in India. This stress build up has also affected the otherwise stable, continental interiors such as the Aravalli – Delhi Fold Belt in NW India that is infested with a network of lineaments developed during its complex and prolonged deformation history. The most plausible explanation for the frequent occurrence of earthquakes in this region seems to be the Neotectonic reactivation of such faults, triggered by the stress build up in the Himalayan region.

Earthquakes along active plate margins and mid oceanic regions can be attributed to degassing related magmatic fluid movement and increased fluid pressure. The high frequency of earthquakes in the intraplate western Indian Deccan Province has been attributed to fluid pressures increase due to penetration of magmatic fluids from upper mantle into the seismogenic lower crust (Singh et al. 2019). The development of localized stress field may be a result of increase in pore pressure due to hydrothermal activity and increase in pressure exerted by magma chambers at shallow depth (Singh et al. 2019 and references therein). Such a possibility seems unlikely in case of Aravalli – Delhi Fold Belt region due to absence of any magma chamber below a thickened crust (Sinha-Roy et al. 1998). Change in water table due to heavy rainfall and consequent rise in pore pressure can also trigger micro-earthquakes of limited extent (Singh et al. 2017). This possibility seems quite unlikely as the NW India is one of the least rainfall regions of India.

Understanding of the plate interior seismicity of Peninsular India would be greatly enhanced if we know about the stress sources simulating earthquakes. Possible stress sources include, (i) those related to the force of collision between Indian and Eurasian plates including the central Indian flexural bulge; (ii) gradients resulting from surface topography and erosion and (iii) sediment load in the Arabian Sea and the Bay of Bengal (Bilham and Srivastava 2003; Roy 2006). These processes, in combination or individually, may contribute in stress building. The NE – SW directed unidirectional stress has been inferred for a large number of earthquakes over the entire Indian shield region (Roy 2006). Such a homogenous stress system over the entire Indian peninsular region seems unlikely and there may be some additional geological factors that would influence the local stress pattern. According to Roy (2006) the only geological process that can generate such a regional stress system would be the formation of a new crust along the NW–SE oriented Carlsberg Ridge – rift system operating in the Arabian Sea. Either way, the possible cause for the earthquakes in the Aravalli Delhi Fold Belt region appears to be the reactivation of old fault systems.

## 6. Conclusions

There is recurrence of low to moderate magnitude earthquakes in the otherwise tectonically stable, Aravalli Mountain Region and along its western margin in the eastern half of Rajasthan State. The western part of the State comprises much younger (Phanerozoic) rocks and some active faults, such as the N-S trending, Kanoi Fault. It can be concluded that the trigger for seismicity in the eastern and western domains of Rajasthan State can be attributed to the continued northward drift of the Indian Plate into Tibet region. Several minor faults in Aravalli Delhi Fold Belt facilitate the stress release in form of frequent low to moderate magnitude earthquakes. Epicenters of all the known major earthquakes of peninsular India lie either on the major lineaments or reasonably close to them (Murthy and Raval 2000). This substantiates a close association of such linear features with earthquake occurrence. However, any quantitative correlation between the two has not been conducted in the 'Stable' Aravalli region so far and we hope that our study might invoke geological interest in the region and eventually a better understanding of causes and mechanism of recurrent earthquake in this region.

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## References

Bakliwal PC, Ramaswamy SM (1987) Lineament fabric of Rajasthan and Gujarat, India. Rec. *Geological Survey of India* 113(7): 54-65.

Bhowmik SK, Wilde SA, Bhandari A, Pal T, Pant NC (2012) Growth of the greater Indian landmass and its assemnbly in Rodinia: geochronologic evidence from the Central Indian Tectonic Zone. *Gondwana Research* 22: 54-72.

Bhushan SK, Chandrasekaran V (2002) Geology and geochemistry of the magmatic rocks of the Malani igneous suite and tertiary alkaline province of western Rajasthan. *Geological Survey of India Memoir* 126: 179 pp.

Bilham, R, Srivastava SK (2003) Preface: The Bhuj Earthquake, Gujarat, India, 2001. *Proceedings Indian Academy of Science* 112: 313-314

Das AR (1988) Geometry of the superposed deformation in the Delhi Supergroup of rocks, north of Jaipur, Rajasthan. In: A.B. Roy (ed), Precambrian of the Aravalli Mountain, Rajasthan, India. *Geological Society of India* 7: 247-266.

Dasgupta S, Pande P, Ganguly D, Iqbal Z, Sanyal K, Venkatraman NV, Dasgupta S, Sural B, Harendranath L, Majumdar K, Sanyal S, Roy A, Das LK, Misra PS, Gupta H (2000) *Seismotectonic Atlas of India and its Environs*, Geological Survey of India, with 43 plates.

de Wall H, Pandit MK, Dotzler R, Just J (2012) Cryogenian transpression and granite intrusion along the western margin of Rodinia (Mt. Abu region): Magnetic fabric and geochemical inferences on Neoproterozoic geodynamics of the NW Indian block. *Tectonophysics* 554-555: 143-158.

Dreger, DS, Tkalcic, H, Johnson, M (2000) Dilation processes accompanying earthquakes in the Long Valley Caldera. Science 288:122-125.

Gregory LC, Meert JG, Bingen B, Pandit MK, Torsvik TH (2009) Paleomagnetism and geochronology of the Malani Igneous Suite, Northwest India: Implications for the configuration of Rodinia and the assembly of Gondwana. *Precambrian Research* 170: 13 – 26.

Gupta SN, Arora Y, Mathur RK, Iqballuddin Prasad B, Sahay TN, Sharma SB (1981) Lithostratigraphic map of Aravalli Region, SE-Rajasthan and Nothern Gujarat. *Geological Survey of India*, Hyderabad.

Gupta SN, Arora Y, Mathur RK, Iqballuddin Prasad B, Sahay TN, Sharma SB (1997) The Precambrian geology of the Aravalli region, southern Rajasthan and northeastern Gujarat. Mem. *Geological Survey of India* 123: 262 p.

Heron AM (1953) Thegeolgy of central Rajputana, Mem. Geological Survey of India 79: 1-389.

Kayal JR (2008) Microearthquake Seismology and Seimotectonics of South Asia, 1st ed. Springer Verlag and Capital Publishing company, India.

Meert JG, Pandit MK (2015) The Archean and Proterozoic history of peninsular India: Tectonic framework for Precambrian sedimentary basins in India. *Geological Society Memoir* 43: 29-54.

Meert JG, Pandit MK, Pradhan Vimal R, Banks J, Sirianni R, Stroud M, Newsteed, Brittany N, Gifford J (2010) Precambrian crustal evolution of Peninsular India: A 3.0 billion year odyssey. *Journal of Asian Earth Sciences* 39: 483-515.

Murthy, YS, Raval, U (2000) Bouguer gravity image of India and the neighbouring ESCAP region: a study of tectonics and natural resources. *Journal of Geophysics* 21: 59–70.

Negi JG, Pandey, OP, Agarwal, PK (1986) Supermobility of hot Indian lithosphere. *Tectonophysics* 11: 135–147.

Pandey DK, Bahadur T (2009) A review of the stratigraphy of Marwar Supergroup of west-central Rajasthan. *Journal of the Geological Society of India* 73: 7474-758.

Pandit MK, Sial AN, Jamrani SS, Ferreira VP (2001) Carbon isotopic profile across the Bilara Group rocks Trans-Aravalli Marwar Supergroup in western India: implications for Neoproterozoic – Cambrian transition. *Gondwana Research* 4: 387-394.

Pareek HS (1984) Pre-quaternary geology and mineral resources of northwestern Rajasthan. Mem. *Geological Survey of India* 115: 99 p.

Pradhan VR, Meert JG, Pandit MK, Kamenov G, Gregory LC, Malone S J (2010) India's changing place in global Proterozoic reconstructions: new geochronologic constraints on key paleomagnetic poles from the Dharwar and Aravalli/Bundelkhand cratons. *Journal of Geodynamics* 50: 224-242.

Rao RUM, Rao GV, Hari Narayan (1976) Radioactive heat generation and heat flow in the Indian Shield. *Earth Planetary Science Letters* 30: 57–64.

Roy AB (2004) The Phanerozoic Reconstitution of Indian Shield as the Aftermath of Break-up of the Gondwanaland. *Gondwana Research* 7 (2): 387-406.

Roy AB (2006) Seismicity in the peninsular Indian shield: Some geological considerations; *Current Science* 91(4): 456-463.

Roy AB, Jakhar SR (2002) Geology of Rajasthan (northwest India) – Precambrian to Recent. *Scientific Publishers (India)*: 421 p.

Singh AP, Koulakov I, Ravi Kumar M, Kumar S, Kayal JR (2019) Seismic velocity structure and intraplate seismicity beneath the Deccan Volcanic Province of Western India. *Physics of Earth and Planetary Interiors* 287: 21 – 36.

Singh AP, Kumar, MR, Kumar S, Sateesh A, Mahesh P, Shukla A, Talukdar R (2017) Seismicity and subterranean sounds in the northwest Deccan Volcanic Province of India. *Bulletin Seismological* 107: 1129–1135.

Singh RN (1985) Thermal structure of the Indian Shield. *Indian Journal of Earth Sciences* 12: 155–158.

Sinha-Roy S (1984) Precambrian crustal interaction in Rajasthan, NW India. In: Proc. Seminar on Crustal Evolution if Indian shiekd and its bearings on Metallogeny. *Indian Journal of Earth Sciences*: 84-91.

Sinha-Roy S, Malhotra G, Guha DB (1995) A transect across Rajasthan Precambrian terrain in relation to geology, tectonics and crustal evolution of south-central Rajasthan. In: S. Sinha-Roy and K. R. Gupta (Eds.) Continental crust of Northwestern and Central India, Mem. *Geological Survey of India* 23: 575-677.

Sinha-Roy S, Malhotra G, Mohanty MK (1998) The Geology of Rajasthan. Bangalore: *Geological Society of India*: 278 p.

Wang W, Cawood PA, Pandit MK, Zhou MF, Chen WT (2017) Zircon U-Pb age and Hf isotope evidence for Eoarchean crustal remnant, and crustal growth and reworking respond to supercontinental cycles in NW India. *Journal of Geological Society*: 174(4): 759 - 772.

Zhao JH, Pandit MK, Wang W, Xia XP (2018) Neoproterozoic tectonothermal evolution of NW India: evidence from geochemistry and geochronology of granitoids. *Lithos* 316: 330-346.