Statistical Study on Seismicity of the Indian Tectonic Plate Interactions

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Abstract
Seismic data over decades needs to be analyzed in order to comprehend tectonic dynamics and seismic hazards along tectonic plate boundaries. However, the study of the Indian tectonic plate, encompassing a homogeneous catalogue and analysis of earthquake data over its boundaries, is sparse in literature. Hence, this study statistically analyzes the seismicity data taken from 1960 to 2023 across the Indian tectonic plate. Gutenberg-Richter parameters are used to understand seismicity rate and magnitude-frequency distribution. Seismic energy, G-R parameters and depth analysis of earthquake data are carried out to statistically analyze five boundary plate intersections. The G-R parameters, seismic energy release and M_c of all zones are calculated and reported in the study.

This study reveals substantial variations in G-R parameters, seismic energy and depth distributions through the boundaries indicating diverse tectonic settings. Also, the shallow seismic events dominate in most zones, with average depths between 14.29 km and 31.44 km, but intermediate and deep events are predominantly located in subduction and convergent zones such as Indian-Burma and Indian-Eurasian, reaching depths over 400 km. The variations in depth, along with seismic energy and G-R parameters, reveal the interaction of rifting, subduction and compressional forces that indicate each boundary. These observations could be useful for ascertaining boundary conditions in 3 D plate modeling.

Keywords: Indian tectonic plate, Seismic energy release, Gutenberg-Richter parameters Seismogenic zones.

Introduction

The recording of earthquakes and studying the earthquake data got started early in the 19th century. The historical and instrumental forms of data are now available in the form of databases. For the Indian context, numerous researchers worked in collecting and analyzing the data[23-28]. There is limited study in literature on collecting and interpretation of earthquake data collected for the Indian tectonic plate boundaries. In the year 2003, Bird[6] provided the boundaries of the 52 tectonic plates spread all over the world. Those tectonic boundaries highlighting the Indian tectonic plate are shown in figure 1. The Indian tectonic plate covers most of the Indian subcontinent and beyond into the Indian Ocean. It includes regions beyond India's borders including portions of Pakistan, Nepal, Bhutan, Bangladesh, Sri Lanka and portion of Myanmar.

As shown in figure 1, the Indian tectonic plate is bordered by the Eurasian plate to the north, where their continuous collision has led to the creation of the Himalayan mountain range and the Tibetan plateau. To the west, it is demarcated by the Arabian plate, with the boundary formed by the Owen fracture zone and the Makran subduction zone. To the south, it connects with the Indian Ocean lithosphere, engaging with the Australian plate at the Central Indian Ridge and the Carlsberg Ridge, regions characterized by significant seafloor spreading. To the east, it is bordered by the Burma microplate and the Sunda plate, with the subduction of the Indian plate beneath these plates resulting in the formation of the Andaman and Nicobar Islands, along with the Java Trench[4,13,19]. An effort is made to study the seismic activities of the Indian tectonic plate by statistical approach, considering the earthquake catalogue spanning from 1900 to 2023.

The boundaries for the Indian tectonic plate are considered in this study as 52˚E-100˚E, longitude and 7˚S-38˚N latitude. The seismicity analysis can provide a more accurate representation of the underlying seismic activity and can facilitate credible evaluations of earthquake occurrence and hazards by isolating the independent events. The process followed is declustering[15,19]. Therefore, the declustered data can be used as the main dataset. The interaction of the Indian tectonic plate with the Eurasian, Arabian, Somalia, Australian and Burma plates can be studied by considering the 5 seismogenic zones as 1, 2, 3, 4 and 5 respectively whereas the intraplate region is considered zone 6.

The outer and interior boundaries of zones are generated by taking 220 kilometers on either side of the Bird's Indian boundary coordinates[6]. The declustered seismic data in each five zone is separated from the main dataset for further analysis. Furthermore, a seismic catalog is considered complete below a threshold magnitude, which is the magnitude's completeness[30]. There are two distinct categories of Mc evaluation methods: catalog-based methods and network-based methods. The maximum curvature (MAXC) method[33] is one of the catalog-based methods that is used in this study. It determines the completeness of the magnitude by identifying the maximum point on the cumulative frequency-magnitude graph.

The intercept (a) and slope (b) of the cumulative frequency-magnitude graph can be used for the assessment of the

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seismicity of a region[3,5,14,20]. Higher values of "a" imply a higher overall frequency of earthquakes, whereas lower values indicate lower seismic activity. A smaller value of "b" indicates that larger earthquakes occur more frequently than minor ones, indicating a greater seismic hazard. These parameters are called Gutenberg-Rider (G-R) parameters, which are useful in the assessment of seismicity of a region and in Probabilistic Seismic Hazard Analysis (PSHA)[16].

The G-R parameters for all five seismogenic zones considered in this study are calculated. Moreover, the seismic energy release of a region is an independent parameter of its seismic activity. The time series generated with the annual seismic energy of a region tells the seismic activity. The seismic energy release considering all events after magnitude completeness is found out by summing up and is used as one of the parameters along with a and b to access the seismicity in this study. Choy and Boatwright[8] empirical equations are used to calculate the seismic energy.

This study aims to compile an earthquake event catalog for the Indian tectonic plate context from various sources until 2023. The statistical study regarding the Indian tectonic boundaries is carried out in this study, which helps in understanding the Indian seismicity. Gutenberg-Richter Parameters, seismic energy and seismicity data are used in this study to access the seismicity of the five boundaries of the Indian tectonic plate, considered in this study. The results reported in this study with further analysis can be useful in developing the boundary conditions for the Indian tectonic plate, which thereby can be used in the development of finite element modeling of the 3D Indian tectonic plate.

Material and Methods

Data: Earthquake data is crucial for studying earthquakes and tectonic plate behavior. Main sources of collecting seismic data are the International Seismological Centre[9] (ISC) (http://www.isc.ac.uk/), the United States Geological Survey[11] (USGS) (https://www.usgs.gov/) and National Center for Seismology[10] (NCS) (https://seismo.gov.in/). Version 10 of the ISC-GEM Catalogue was released in March 2023 and compared to data. The dataset after data cleaning, preprocessing and processing comprises of seismic events with Mw > 1 from 01/01/1900 to 31/12/2022. The conversion of events from different magnitude scales into moment magnitude is done by using an empirical equation suggested by Scordilis[31].

Declustering: Earthquake catalogues often contain clusters of events that can bias statistical analysis and hinder an accurate assessment of seismic hazards. The process of declustering is to separate mainshocks, which are the primary earthquakes in a sequence, from aftershocks, which are lesser seismic events that occur subsequent to the mainshock. Various methodologies and strategies are employed for the purpose of declustering earthquake catalogs. In general, these methodologies consider the spatial, temporal and magnitude characteristics of earthquakes in order to ascertain their correlation and effectively distinguish them. The Gardner and Knopoff method[15] and the Reasenberg method[29] are widely utilized declustering strategies in the field.

The researchers Aki[2], Knopoff[22], Gardner and Knopoff[15] and Reasenberg[29] also presented designated space-time lengths as a function of the magnitude of the mainshock for the purpose of detecting aftershocks. However, they urged readers to explore alternative values for experimentation. Gardner and Knopf's algorithm[15] is used to decluster the catalog in this study and is shown in figure 2a.

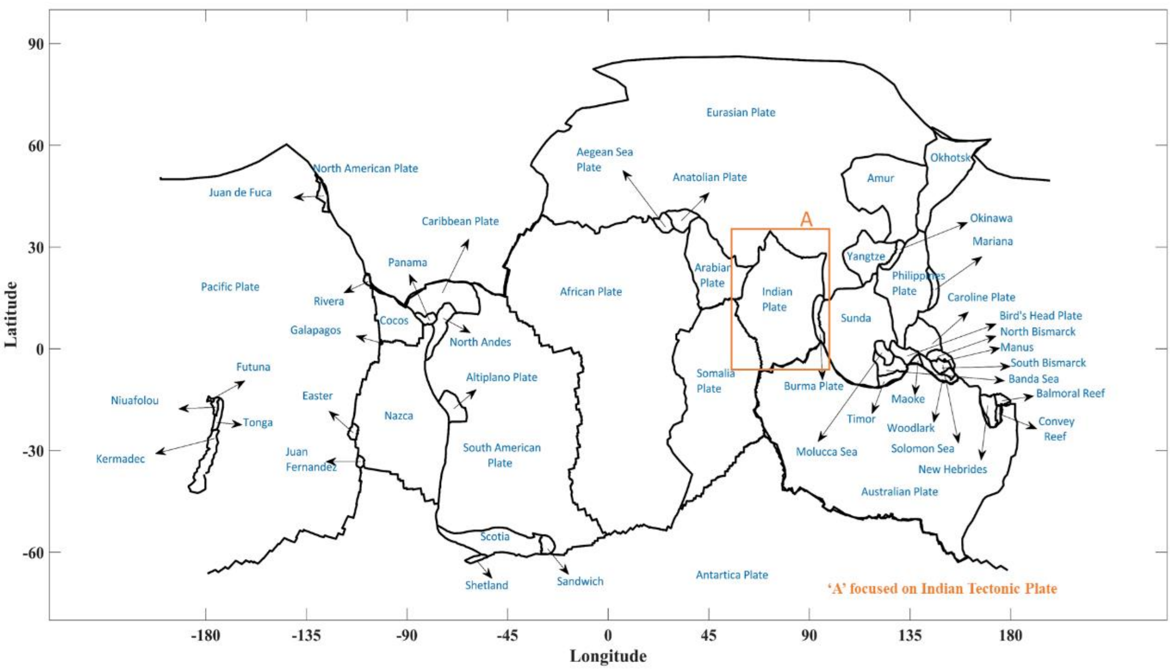


Figure 1: A representation of 52 tectonic plates distributed globally, with focus on the Indian tectonic plate (A)

Figure 2 shows the non-uniform catalogue because of the absence of the events from the time span of 1900 to 1960, which is not the reason for the absence of events but the absence of recoding stations at those times. The events with higher magnitudes are managed to be collected from the available literature and surveys for those spans. From 1960 to 2000, it was noticed that data of magnitudes greater than 3 was well recorded because of the development of stations.

Magnitude Completeness (M_c): The maximum curvature (MAXC) method[32,33] is used to determine the completeness of magnitude by identifying a point on the cumulative frequency-magnitude plot where curvature reaches its peak. It offers an objective approach for establishing the threshold beneath which an earthquake catalog is considered incomplete. The Maximum Curvature Method adapts to fluctuations in seismicity patterns due to its sensitivity to significant changes in earthquake frequency. It is flexible and adaptable, applicable to various seismicity datasets and regions. It has been widely utilized in seismicity research and is referenced in scientific literature, indicating its effectiveness and reliability. The catalog is updated to ensure completeness and uniformity, as shown in figure 2b.

Seismicity Parameters: In 1944, Gutenberg et al[16] noted a correlation between the magnitude and frequency of California earthquakes and proposed a logarithmic relationship between earthquake magnitudes and their occurrence rates. Later, in 1956, they introduced the now-named Richter magnitude scale and refined and expanded Gutenberg's work. The quantity of earthquakes of a given magnitude is inversely proportional to the magnitude itself, according to the Gutenberg-Richter[16] law. In other terms, there are significantly more minor quakes than major ones.

The law can be expressed mathematically as:

$$\log(N) = a - b*M \quad (1)$$

where N is the number of earthquakes with a magnitude equal to or greater than M, a and b are constants.

The equations used to calculate seismic moment and seismic energy are:

$$log_{10}(M_o) = 1.5(M_w + 6.0) \quad (2)$$

$$E_s = 1.6 * 10^{-5} M_o \quad (3)$$

as suggested by Hanks and Kanamori[17] and Choy and Boatwright[8] respectively.

Defining Boundaries: Bolt[7] in 2005 proposed that the majority of earthquakes occur along interplate tectonic plate boundaries. Kavitha and Raghunath's[21] regional seismic energy release forecasts reveal that plate intersections are the primary earthquake locations worldwide, while earthquakes inside tectonic plates are infrequent. These plate intersection seismic activity patterns require further study. The interaction between two tectonic plates is named as "Seismogenic zone." Since the Indian tectonic plate is bound by five tectonic plates, the plan divides it into five seismic zones. Zone 1 is where the Indian plate intersects the Eurasian Plate and zone 2 is where it meets the Arabian plate. Zones 3, 4 and 5 are where the Indian plate meets the Somalia, Australian and Burma plates as shown in figure 3.

Results and Discussion

The declustered data of the Indian tectonic plate has documented 28,866 instances of earthquake events, with the majority of them, specifically 89.4%, being classified as shallow events i.e. those that occur at depths less than 70 km. Intermediate events, which are those that occur at depths ranging from 70 km to 300 km, account for a mere 0.1%, or 3,050 of the total events. Lastly, deep events, which are those that occur at depths greater than 300 km, account for a mere 0.07%, or 20 of the total events. The results regarding the depth in all the seismogenic zones are reported in table 1 Among the 28,866 events under consideration, a majority of 25,379 events fall within the magnitude range of 3.8 to 5 (Mw), while 3,215 events fall within the range of 5 to 6. Smaller number of events, specifically 246, are observed within the range of 6 to 7.

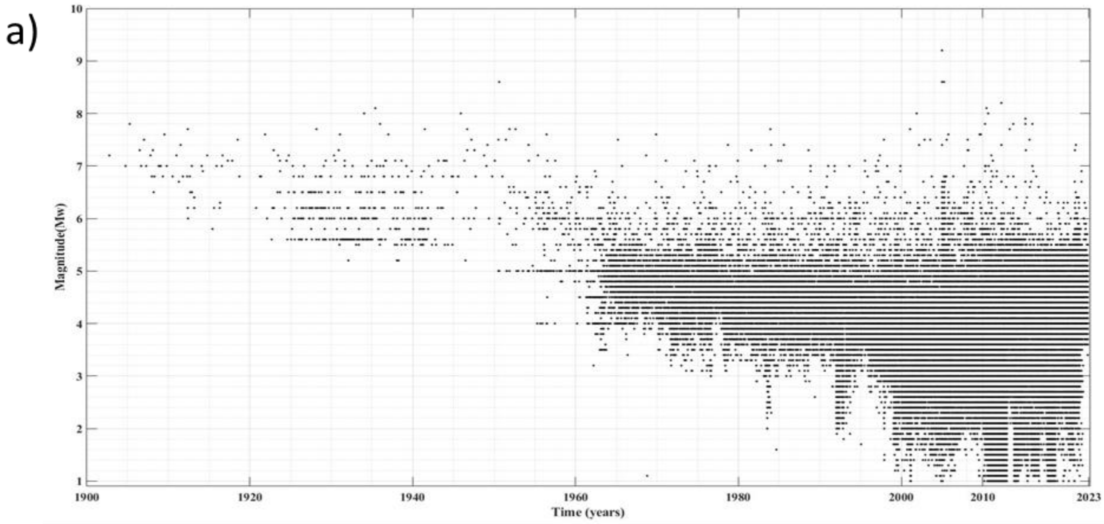
23 events are observed in the range between 7 and 8, while only 2 events are observed within the range of 8 to 9. Finally, a single event with a magnitude greater than 9 is observed. This suggests that relatively smaller-magnitude earthquakes are more frequent in the region. There are fewer events of higher magnitudes, with a sharp decline observed beyond magnitude 6. The data shows that only a small number of earthquake events reach higher magnitudes. This indicates that powerful earthquakes are rare occurrences in the tectonic plate. The spatial distribution of earthquake events along with the tectonic plate considering magnitude variation and depth variation is shown in figures 4 and 5 respectively. Figures 4 and 5 clearly demonstrate the concentration of higher magnitude events and deep events along the plate boundary, specifically along the interactions between the Indian-Eurasian and Indian-Burma plates. The statistical data in the form of histograms for magnitude and depth variation is shown in figures 6a and 6b.

More powerful events can be expected in these regions because of the deep tectonic activity involved. An in-depth analysis is required in these regions. Comparatively, the intraplate region is not that seismically active; still, the study for the intraplate region is needed because events of moderate magnitude with shallow depth can create significant damage. Seismogenic zones 1, 2, 3, 4 and 5 are where the Indian plate interacts with the Eurasian, Arabian, Somalia, Australian and Burma plates, while zone 6 is the intraplate zone. The G-R parameters for the Indian tectonic plate are found to be a = 7.408, b = 0.7597 and Mc = 3.8. The G-R parameters were found as a = 6.6947, b = 0.6951; a = 9.4060, b = 1.5125; a = 7.0161, b = 0.8662; a = 6.2455, b = 0.7760; a = 7.1974, b = 0.8131; a = 5.9305, b = 0.6816 for seismogenic zones 1, 2, 3, 4, 5 and the intraplate zone considered in this study respectively.

The magnitude completeness (M_c) values for seismogenic zones 1, 2, 3, 4, 5 and the intraplate zone were found to be 3.8, 4.8, 4.3, 4.3, 4 and 3.8 respectively shown in Table 2. The seismic energy (J) per square km is calculated by adding all seismic energies considering the above Mc value events from 1960 to 2022 and is found to be $1.86 * 10^{10}$ J/km^2, $1.70 * 10^8$ J/km^2, $3.18 * 10^9$ J/km^2, $2.89 * 10^{10}$ J/km^2, $1.22 * 10^{12}$ J/km^2 and $7.57 * 10^8$ J/km^2 for zone 1, zone 2, zone 3, zone 4, zone 5 and intraplate zone, respectively.

Differences in seismic energy output between zones reflect the complicated tectonic interactions occurring at the boundaries of the Indian Plate with other plates. The most intense seismic activity occurs in zones 1, 4 and 5, which coincide with the plate borders of the Eurasian, Australian and Burma Plates. Greater plate interaction and the potential for more severe earthquakes are features of these regions. Zone 2, which represents the boundary with the Arabian Plate, has substantially lower energy releases compared to zone 3, which represents the boundary with the Somalia Plate. Seismic events can occur within the plate's interior due to internal stresses and fault systems, as evidenced by the intra-plate zone's substantial seismic activity despite being within the Indian Plate. Events catalogue, Magnitude completeness (M_c) Graph and Annual seismic energy time series for seismogenic zone 1 are shown in figures 7a, 7b and 7c.

Indian-Eurasian: This zone reported 11,309 events, characterized by a high seismicity rate, predominantly consisting of shallow occurrences (8,972), which represent about 80% of the total. According to table 2, the average depth for shallow occurrences is 27.25 km, signifying considerable crustal deformation. Intermediate events (2,324) significantly contribute, with an average depth of 111.78 km, indicative of activity inside the subducting slab.



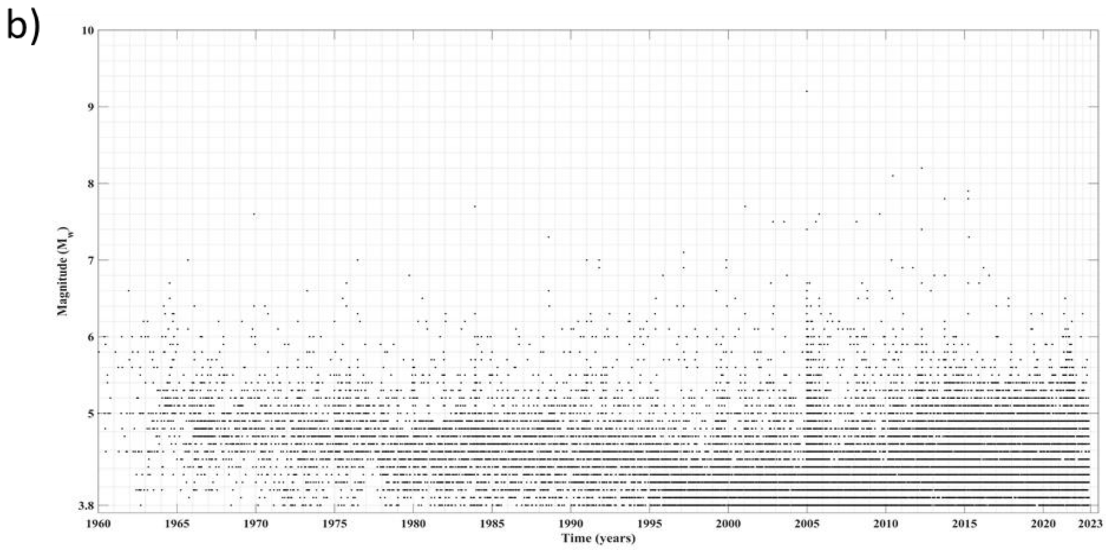


Figure 2: Indian Catalogue (52˚E-100˚E, 7˚S-38˚N) spanning from a) 1900 to 2022 and b) Homogenous catalog spanning from 1960 to 2022, with M_c as 3.8

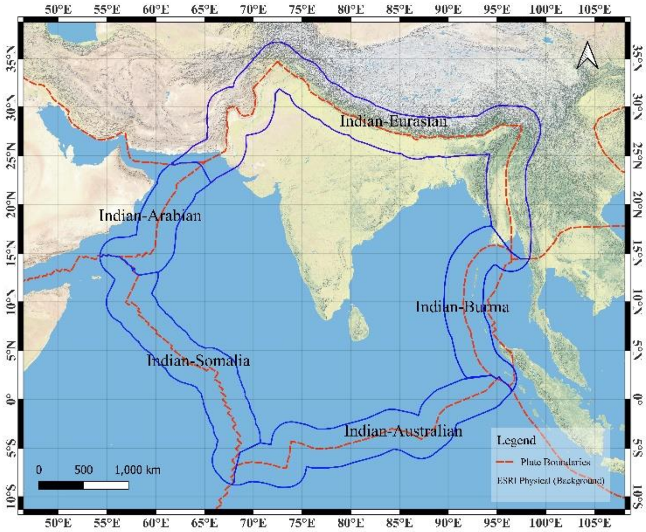


Figure 3: Five seismogenic zones of the Indian tectonic plate considered in this study

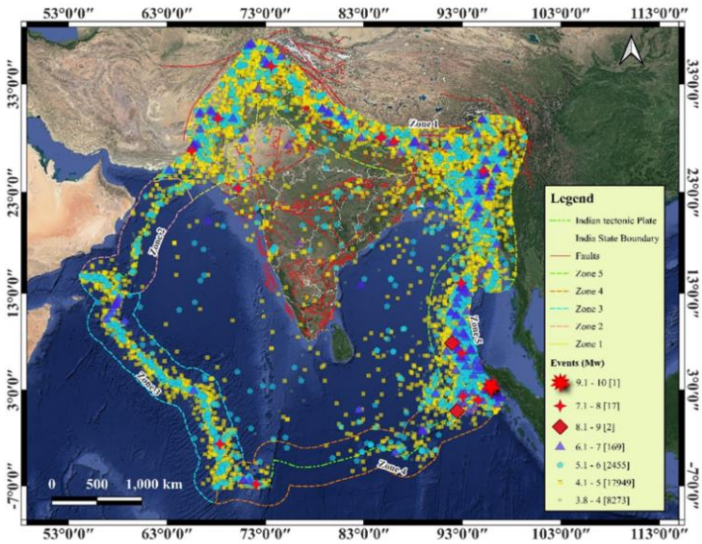


Figure 4: Epicentral distribution of earthquake events showing variation in magnitudes

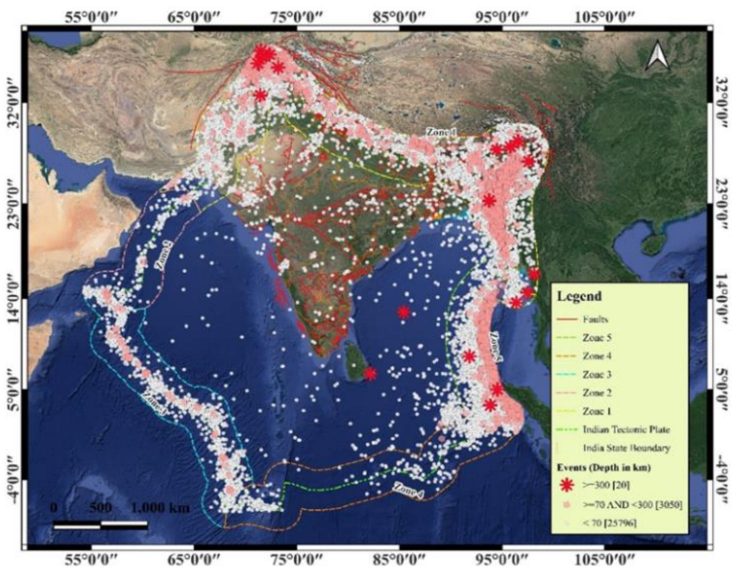


Figure 5: Epicentral distribution of earthquake events showing variation in depths

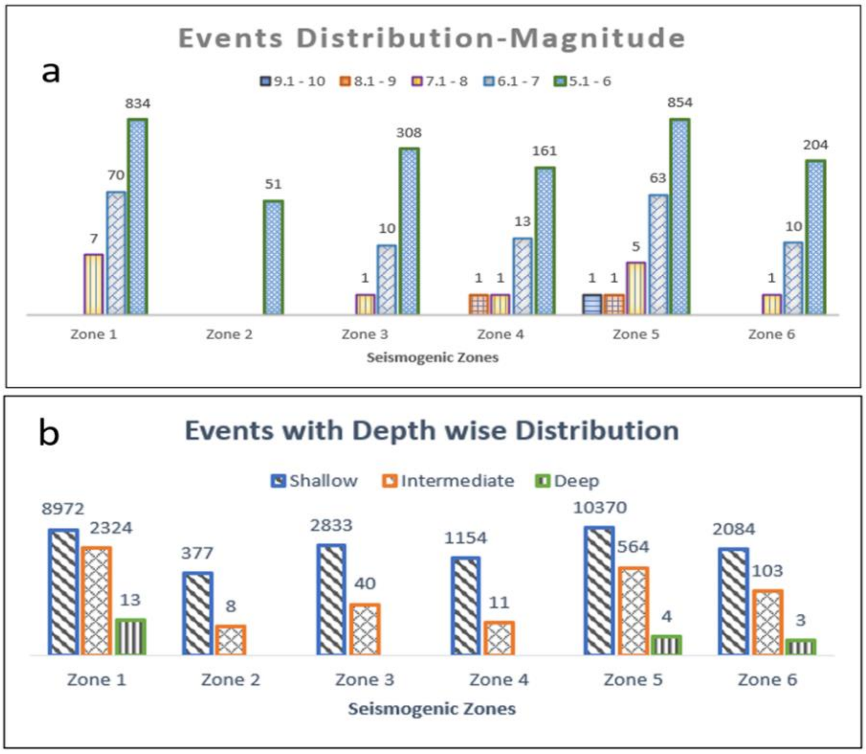


Figure 6: Statistical events distribution in a) Magnitude wise b) Depth wise

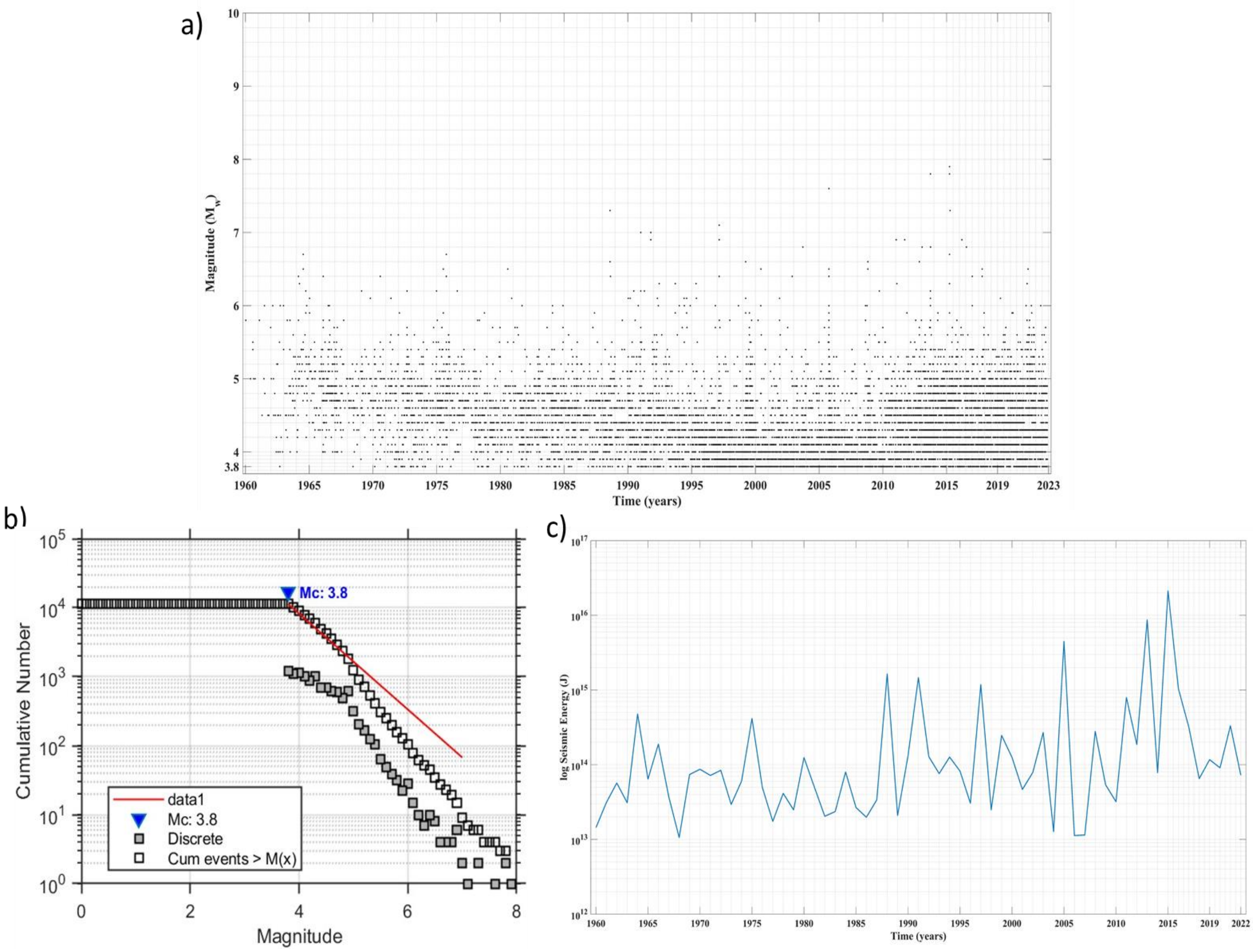


Figure 7: a) Events catalogue spanning from 1900 to 2023, b) Magnitude Completeness (M_c) graph and c) Annual seismic energy time series for seismogenic zone 1

Table 1
Zone-wise representation of declustered data based on depth variation

Plate Boundary	Total Events	Shallow Events		Intermediate Events		Deep Events	
		Number of Events	Avg. Depth (km)	Number of Events	Avg. Depth (km)	Number of Events	Avg. Depth (km)
Indian-Eurasian	11309	8972	27.25	2324	111.78	13	439.35
Indian-Arabian	385	377	19.44	8	85.35	0	-
Indian-Somalia	2873	2833	14.29	40	123.95	0	-
Indian-Australian	1165	1154	15.30	11	119.29	0	-
Indian-Burma	10938	10370	31.44	564	97.41	4	474.23
Intraplate	2190	2084	25.17	103	98.83	3	438.33

Deep events are infrequent (13), although they possess the highest average depth of 439.35 km, presumably associated with intricate interactions at greater depths. This extensive depth distribution signifies a variety of tectonic events, ranging from crustal collisions to deep subduction dynamics. In the Indian-Eurasian region, the M_c value of 3.8 supports the accounting of smaller earthquakes, allowing for a comprehensive frequency-magnitude analysis. The a-value of 6.6947 indicates moderate seismic activity; however, the low b-value of 0.695 implies a greater prevalence of large-magnitude earthquakes.

The seismic energy output of 4.59×10^{16} is substantial, resulting from the active tectonic collision between the Indian and Eurasian plates. The seismic energy density of 1.86×10^{10} J/km^2 underscores the intense seismic activity in this area. The low b-value coincides with significant energy release, suggesting that major earthquakes mostly contribute to the energy, even with the presence of lesser events.

Indian-Arabian: This zone exhibits the lowest events (385), characterized by a significant prevalence of shallow events (377), with an average depth of 19.44 kilometers. Intermediate events (8) are few and occur at an average depth of 85.35 km. No significant seismic events are documented in this area, indicating that seismic activity is restricted to the crust and uppermost mantle, in accordance with the region's relatively inactive tectonic regime. The shallower depths suggest lower subduction or collisional forces relative to other regions. The Indian-Arabian region demonstrates a M_c value of 4.8, indicating the exclusion of minor earthquakes from the dataset, hence emphasizing larger seismic occurrences. A notably significant a-value of 9.406 indicates an exceptionally high frequency of earthquakes; nevertheless, the substantial b-value of 1.5125 suggests that most of these events are of lesser size. Thus, the seismic energy release is comparatively minimal at 1.10×10^{14} J, accompanied by a seismic energy density of 1 70×10^{8} J/km^2, the lowest across all zones. The association between the higher b-value and lower energy release indicates the prevalence of smaller earthquakes.

Indian-Somalia: The Indian-Somalia documented 2,873 events, with a predominant 98.6% categorized as shallow (2,833), with an average depth of 14.29 kilometers, the shallowest of all zones. Intermediate events are infrequent (40), occurring at an average depth of 123.95 km. No profound seismic events are detected, supporting the view that tectonic activity is confined to the upper crust and lithosphere. The prevalence of shallow occurrences suggests restricted subduction activity and mostly extensional or transform faulting mechanisms. In the Indian-Somalia region, a M_c value of 4.3 supports the recognition of moderate to major earthquakes. The a-value of 7.016 indicates considerable seismic activity, while the b-value of 0.8662 reflects a balanced distribution of minor and major earthquakes. The seismic energy release is moderate, measuring 4.29×10^{15} J, whereas the seismic energy density is 3.18×10^{9} J/km^2. The balanced b-value indicates that both minor and major earthquakes substantially contribute to the overall energy release, signifying a dynamic but moderately active tectonic setting.

Indian-Australian: This zone, with 1,165 total events, exhibits a pattern similar to zone 3, characterized by a predominance of shallow events (1,154), with an average depth of 15.30 km. Intermediate events are infrequent (11), with an average depth of 119.29 km and no deep events are recorded. The limited seismic activity indicates that mechanisms of crustal and lithospheric deformation are predominant, perhaps related to transform faults or divergent plate boundaries. The Indian-Australian zone, with a M_c value of 4.3, encompasses moderate to major earthquakes. The a-value of 6.245 signifies moderate seismic activity; however, the low b-value of 0.776 suggests a higher chance of larger earthquakes. The substantial seismic energy release of 4.45×10^{16} J and the high seismic energy density of 2.90×10^{10} J/km^2 are indicative of this recurring occurrence. The relationship between the low b-value and high energy release indicates that larger events significantly affect energy output, in accordance with the tectonic activity at this boundary.

Indian-Burma: This zone contains 10,938 events, comparable to zone 1 regarding earthquake activity. Shallow events (10,370) are prominent, showing an average depth of 31.44 km, the highest throughout the zones. Intermediate events (564) occurred at an average depth of 97.41 km, indicating substantial subduction-related activity. Deep events are infrequent (4), yet demonstrate the highest average depth across all zones at 474.23 km, demonstrating subduction processes extending deep into the earth's crust.

Table 2
Magnitude- recurrence and maximum magnitude values for each source zone

Plate Boundary	M_c	G-R Parameters		Seismic Energy (J)	Seismic Energy (J)/Area (Km2)
		a	b		
Indian-Eurasian	3.8	6.6947	0.6951	4.59E+16	1.86E+10
Indian-Arabian	4.8	9.406	1.5125	1.10E+14	1.70E+08
Indian-Somalia	4.3	7.0161	0.8662	4.29E+15	3.18E+09
Indian-Australian	4.3	6.2455	0.776	4.45E+16	2.90E+10
Indian-Burma	4	7.1974	0.8131	1.05E+18	1.22E+12
Intraplate	3.8	5.9305	0.6816	6.94E+15	7.57E+08

The considerable depth range indicates active subduction and complex tectonics, with shallow events prevailing due to crustal deformation close to the trench. The Indian-Burma zone is reported with a M_c value of 4.0, aiding the incorporation of a diverse array of earthquake magnitudes. The a-value of 7.197 signifies high seismic activity whereas the comparatively low b value of 0.813 suggests a substantial frequency of large-magnitude events. This region demonstrates the greatest seismic energy release, quantified at 1.05×10^{18} J, alongside an extraordinarily high seismic energy density of 1.22×10^{12} J/km^2. The low b-value has a strong correlation with the substantial energy release, as larger earthquakes prevail in this tectonically active zone. The higher a-value indicates the region's overall high frequency of seismic activity.

Indian Intraplate: The intraplate zone, with 2,190 events, is characterized by shallow seismicity (2,084) with an average depth of 25.17 km. Intermediate events (103) occur at an average depth of 98.83 km, while deep occurrences are rare (3), with an average depth of 438.33 km. This pattern aligns with an intraplate context, wherein the majority of seismic activity arises from the accumulation and release of crustal stress. The occurrence of rare intermediate and deep events indicates constrained regions of lithospheric delamination. The intraplate zone, identified by a M_c value of 3.8, encompasses minor earthquakes, hence providing a more extensive dataset. The a-value of 5.93 is the lowest among all zones, showing relatively less seismic activity.

The exceptionally low b-value of 0.6816 indicates a greater prevalence of large-magnitude earthquakes which significantly influence the moderate seismic energy release of 6.94×10^{15} J. The seismic energy density is 7.57×10^{8} J/km^2, indicating a somewhat inactive tectonic setting. The correlation between the low b-value and moderate energy release highlights the impact of larger earthquakes in intraplate regions, characterized by infrequent yet significant seismic activity.

Conclusion

This study of seismic characteristics and event depths across the Indian tectonic plate has offered essential insights into the tectonic processes of its distinct plate boundaries. The Gutenberg-Richter parameters, 'a' and 'b' values, are used in understanding the seismicity rate and magnitude-frequency distribution. Seismogenic zones identified by higher 'a-values,' including the Indian-Burma and Indian-Arabian boundaries, demonstrate considerable seismic activity whereas variations in 'b-values' represent distinct stress regimes, with lowered values indicating compressional conditions (e.g. Indian-Eurasian boundary) and higher values suggesting extensional or transform settings (e.g. Indian-Arabian boundary).

The investigation of seismic energy release demonstrates diverse patterns with the Indian-Burma boundary exhibiting the greatest energy dissipation, signifying strong tectonic activity. A board analysis was further carried out to emphasize the depth distribution of seismic activity. Shallow events predominate in most regions, especially in extensional regions such as the Indian-Somalia and Indian-Arabian boundaries, indicating lithospheric extension and rifting.

Intermediate and deep seismic events, predominantly detected in subduction zones such as the Indian-Burma, highlight the dynamics of subduction and the penetration of slabs into the earth's crust. The Indian-Eurasian collision zone displays significant seismic activity which may indicate crustal thickening and intracontinental displacement due to its convergent boundary. The combination of these depth patterns with energy data assists in the identification of active tectonic processes; hence, it will be used in the identification of suitable boundary conditions for the 3D finite element modeling (FEM) simulations of the Indian tectonic plate.

Bringing together seismic energy, magnitude-frequency parameters and depth distributions establishes a comprehensive framework for ascertaining boundary conditions in FEM software such as Pylith (Aagaard et al[1]) and Abaqus etc. Fixed boundaries are suited for high-energy, compressional and subduction zones like the Indian-Eurasian and Indian-Burma regions respectively, while sliding or free conditions better portray extensional zones like Indian-Somalia.

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