THE INTERNATIONAL CONFERENCE ON THE 120TH ANNIVERSARY OF THE BULNAY EARTHQUAKE: ADVANCES IN ASTRONOMY AND GEOPHYSICS

SEISMICITY and SEISMIC REGIME IN WESTERN REGION OF MONGOLIA (Altay region)

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ABSTRACT

This study aims to investigate the seismic regime in Western Mongolia, a tectonically active region characterized by complex geological structures and significant historical and instrumental seismicity. By analyzing earthquake distribution, magnitude, depth, and recurrence patterns, as well as tectonic fault systems and crustal deformation data, the study provides a comprehensive understanding of seismic activity in the region. The dataset includes historical moderate-to-strong earthquakes that occurred between 1900 and 1963, as well as instrumental data from 1964 to 2024 for earthquakes with magnitudes greater than 0.5. Seismic activity and recurrence patterns in the region were analyzed. The key parameters describing the seismic behavior-the a and b values-were estimated using the Gutenberg–Richter law. Additionally, the statistical probability of earthquake occurrence over 60-year and 27-year periods was calculated using the Poisson distribution.From 1964 to 2024, Mongolia seismic network stations recorded more than 167063 earthquakes with magnitude from 0.5 to 7.3 in western region. At this time, around 111152 events with M>1, 22426 events with M>=2.0, 2516 events with M>=3.0, 260 events with Ml>=4.0, 40 events with Ml>=5.0, 5 events with Ml>=6.0 and 2 event with Ml>=7.0 (shown in Graph 3). In Fig 6 shows magnitude-frequency relation. We used all data with magnitude more than 1.0 recorded between 1964 and 2024. Magnitude interval was choose as Md=0.1. Data completeness is at magnitude Mc = 1.4. At the scale of whole Mongolia, we estimated a rather low b=0.758 value and high seismic activity a=5.86. This low b value shows the frequently occurrence of large earthquakes in Mongolia, even since 1964.According to estimates by the Institute of Astronomy and Geophysics (IAG), in the Altay region from 1964 to 2002, the Gutenberg–Richter parameters were a = 5.2 and b = 0.7 for magnitudes M ≥ 2.0. These results show that the b-value remained approximately the same, while the seismic activity slightly increased, as indicated by the higher a-value. In the future, the seismic situation in the western region can be studied in connection with seismic activity along active faults, which may provide an opportunity to forecast the probability of strong earthquakes.

MAP OF SEISMICITY IN MONGOLIA AND BORDER'S REGION

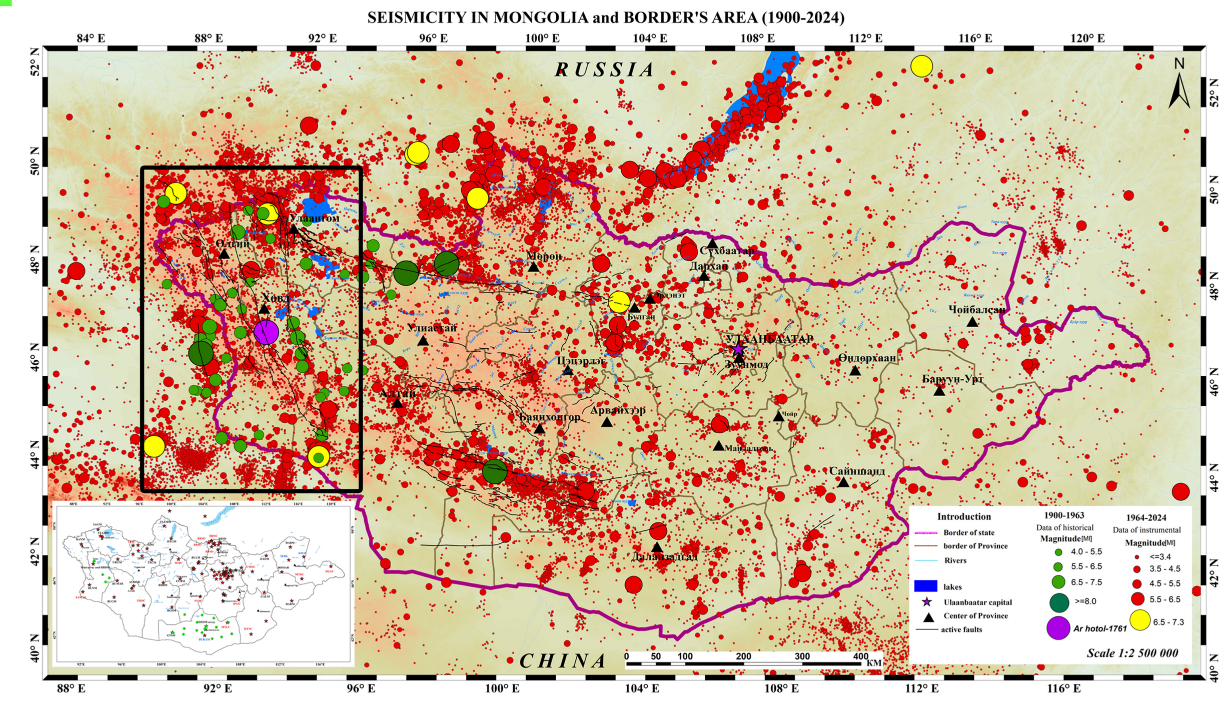


Fig 1. Seismicity in Mongolia and border's area (1900-2024, Ml>=3.5). Black box: study area (/Western region of Mongolia)

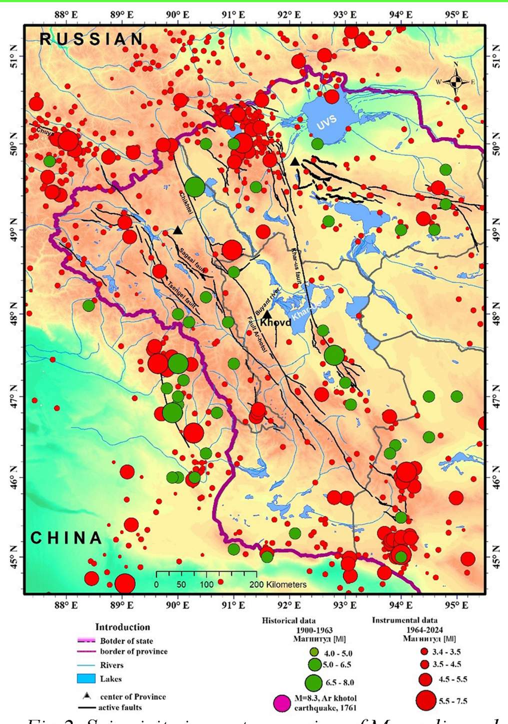


Fig 2. Seismicity in western region of Mongolia and border's area (1900-2024, Ml>=3.5)

INTRODUCTION

Mongolian Altay mountain belt trends northwest-southeast an is cut by an anastomosing network of north-northwest- to northwest- trending faults. Along the northeast flank, a sharp break in slope separates the range from the Ikh Nuuryn Hotgor and implies recent faulting [3]. The main style of faulting in the Mongolian Altay appears to be right-lateral strike slip on planes trending north-nortwest [3]. In the Mongolian altay range, Historical largest erathquake was occurring in 09th, December, 1761, Mw=8.3, surface ruptures is prominent, continuous along more than 215km, This fault name is Ar-hotol. This fault is passing through in the distance around 30km from Khovd city [6]. In the XX century, was occurring 4 largest earthquakes in west part of Mongolia; the Tsetserleg and Bolnay (M8.1, 1905/07/09, M8.3, 1905/07/23), Fu-Yun (M8.0, 1931), Govi-Altai (M8.1, 1957) [8]. In western region, several major structures have been ruptured by two large destructive earthquake in the last century; the Fu-Yun (M8.0, 1931) mainly rigth-lateral strike-slip fault and the Ureg-Nuur (M7.0, 1970) which presents mainly compressive motion [6]. In Altay-Sayan region, The Chuya earthquake occurred in Gorny Altay in September 27, 2003 (Ms=7.3). It is largest event in the Altay-Sayan region at least for last 40 years [8]. Also, have a lot of large faults with seismic activity; Khovd province: Zona Jargalant mountain, Sutai, Zereg basin, activity zona Munkhkhairhan, Tsambagarav and Altankhukhii; Uvs province: Ureg-nuur, Tsagaan shuvuut, Kharkhiraa, Turgen mountains; Ulgii: Achit-nuur, Tolbo, Sagsain, Deluun; North Altai range: Chuya activity zona [8]. The instrumental seismological study of Mongolia started in 1957, just before the large Gobi-Altay earthquake (December 4, 1957, Mw = 8.1). At the beginning, it was installed two permanent stations, one at the capital Ulaanbaatar (1957) and the other at the Altay city (1958), west of Mongolia. In years 1960th, four new stations were installed (Tsetserleg and Tosontsengel in 1964, Khovd in 1965, Dalanzadgad in 1969) and later the network was increased by another four stations until 1988 (Bulgan in 1973, Hatgal in 1975, Ulaangom in 1987, Ulgii in 1988). The seismic stations have been located in region with high seismic activity [8]. In this paper, we will about seismicity of west of Mongolia, describe activity and regime of western regional, estimated a-value and b-value, Magnitude of completeness, shown map seismicity rate on the faults of western region.

THEORETICAL FOUNDATIONS

1.a and b value

An important way to understand the time evolution of the seismicity in various regions is to test the variation of b and a value of G-R law at the scale of whole Mongolia and for specific regions (local areas). To analyze the seismic activity, we used the Gutenberg Richter relation:

$$logN = a - bM \quad (1)$$

Where: M is the minimum magnitude in the data sample. N cumulative number of events in a time intervals with magnitude larger than or equal M; "b" and " a" are constants (Gutenberg and Richter 1944). Generally, the b value will show how the stress changes relative to the tectonic behavior of the region. Scholz (1968) and Wyss (1973) indicated that an increase in stress induces a decrease of the b value. Richter-Gutenberg mentioned that the b value more related to the tectonic behavior rather than to the seismic level. Generally, at the world scale, b value is stable and is around 1 [1]. The a value characterizes the level of seismicity in a region. In contrast to the b value, avalue can vary strongly spatially since it depends more on the density of the seismicity than on the tectonic behavior. Two main methods are used to estimate the b value, which are the least square estimation and the maximum likelihood methods. The method used in this study is Utsu's maximum likelihood methods, which maximize the number of events, used.

2. Poisson distribution and seismic probability

In probability theory and statistics, the Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time if these events occur with a known constant mean rate and independently of the time since the last event.[5] It can also be used for the number of events in other types of intervals than time, and in dimension greater than 1 (e.g., number of events in a given area or volume). The Poisson distribution is named after French mathematician Siméon Denis Poisson. It plays an important role for discrete-stable distributions. The Poisson is a fundamental stochastic model used to describe the occurrence of random events over time or space. Understanding the Poisson distribution allows for the estimation of the probability of a given number of events occurring within a specified interval, as well as the probability distribution of the time until the next event. This makes the model particularly valuable and relevant for scientific analysis and practical applications, especially in fields such as seismology, queueing theory, telecommunications, and reliability engineering [5]. A Poisson distribution is a discrete probability distribution, meaning that it gives the probability of a discrete (i.e., countable) outcome. For Poisson distributions, the discrete outcome is the number of times an event occurs, represented by k. Poisson distribution formula [5]:

$$P(k,\lambda) = e^{-\lambda} * \frac{\lambda^k}{k!} \quad (2)$$

Where:

- $P(k;\lambda)$ -the probability of observing exactly k events
- λ -the expected (mean) number of occurrences in a given interval
- e — the base of the natural logarithm (approximately 2.718)
- k — the number of times the event occurs (non-negative integer)
- k! — factorial of k

THE DATABASE CREATION and SURVEY METHODOLOGY

Mongolia is a seismically active region and main seismicity is caused by active continental deformation in the India-Asia collision zone. Last century, several strong continental seismic events took place in Mongolia. Two of them are well known in the world and these earthquakes occurred in 1905 and 1957, respectively. Due to these strong seismic events, Bulnay and Bogd faults were formed. Moreover, there are several inactive and active faults in Mongolia [2]. From the earthquake database of the National Data Center of the Institute of Astronomy and Geophysics of the Mongolian Academy of Sciences, a database was created for the in this work by selecting from the earthquake data that occurred in the western region from a historical (1900-1963) and instrumentel data (1964-2024). Seismicity of the western region of Mongolia is shown in *Fig 2*.

a.Seismicity of Mongolia and border's area

Seismicity of Mongolia is divided into two parts, a historical part before 1963 years and an instrumental part after 1963 years. (*see fig 1*).

During last century, Mongolia has been one of the most seismic active intracontinental regions in the world with several very largest earthquakes. Since 1900, occurred thirty earthquakes with magnitude M≥7, four of them with magnitude M≥8: Tsetserleg 1905, 190 km of surface rupture; Bolnay 1905, 455 km; Fu-Yun 1931, 180 km; Gobi-Altay 1957, 270 km [8].

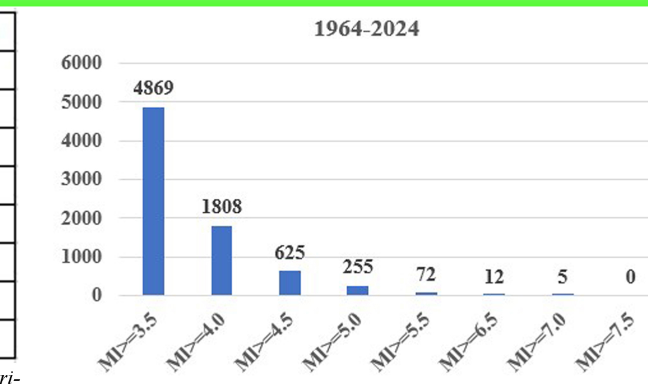
From 1900 to 1963 are reported more than 300 earthquakes with magnitude between 3.5 and 8.3 including the 4 largest events. The occurrence of the largest earthquakes; four earthquakes with magnitude M≥8, eight events with M≥7.0 and several tens earthquakes with magnitude M≥5.5 [8].

G-R relation calculated with magnitudes M > 5 between 1902 and 2002. We can observe two different slopes that illustrate the anomalous occurrence of magnitude M≥8. We obtained a = 6.3 and b = 0.8 for magnitudes between 5 and 7 and a = 5.1 and b = 0.6 for magnitude including M=8. This low value of b is consistent with a relatively high number of large earthquakes and parameter "a" characterizes the number of events [8].

Also, from 1964 to 2024 about 4870 earthquakes with magnitudes greater than 3.5 occurred in territory of Mongolia border's area (*see Table 1, Graph 1 and Fig 1*). Khovd /Arhotol/ fault region: largest earthquake, December 09, 1761, Mw=8.3, rupture distance 215km. (С.Д.Хилько, 1985)

type M	1964-2024
Ml>=3.5	4869
Ml>=4.0	1808
Ml>=4.5	625
Ml>=5.0	255
Ml>=5.5	72
Ml>=6.5	12
Ml>=7.0	5
Ml>=7.5	0

Table 1. Statistic Ml>=3.5 occurred in territory of Mongolia border's area (1964-2024)



Graphic 1. Magnitude distribution of earthquakes of Mongolia from 1964 to 2024

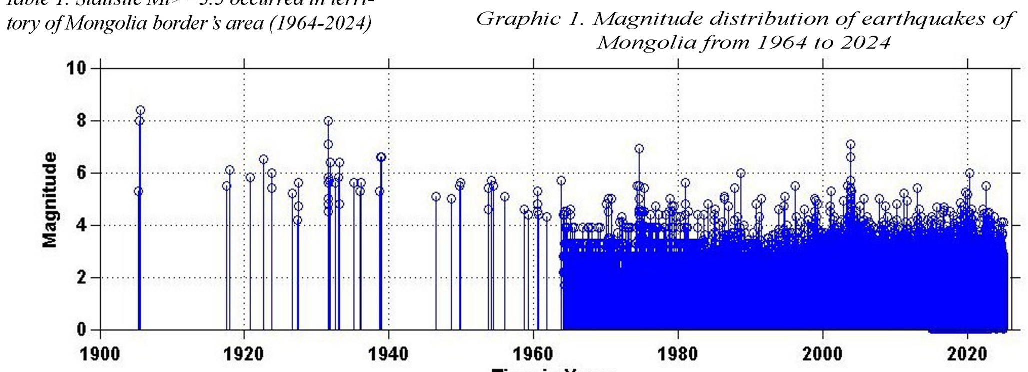


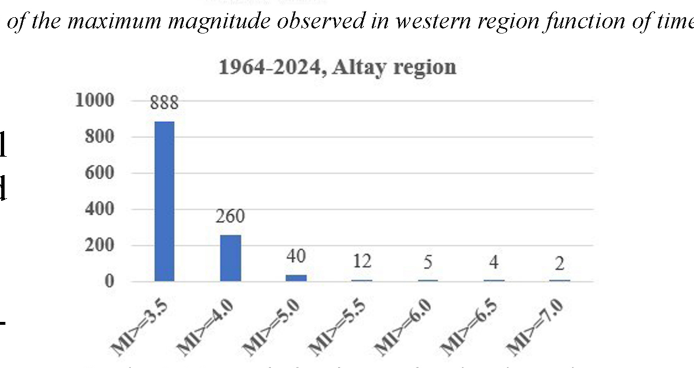
Fig 3. Distribution of the maximum magnitude observed in western region function of time.

b.Seismicity of the western region of Mongolia (Altay region)

The Altay region is one of the seismic active regions of Central Asia. Since 1900 occurred in the region around 100 earthquakes with magnitude more than 5.5 and several earthquakes produced surface ruptures and landslides such as during Fun-Yun, Ureg-Nuur, Tahiin-Shar and Chuya earthquakes (see Graph 2 and Fig 3). Between 1964 and 2024, about 30% of known earthquakes in Mongolia occurred in Altay region including two event with magnitude 7.0 and five with magnitude 6.0.

In Fig 2, Shown of distribution of the maximum magnitude observed in western region function of time.

Also, from 1964 to 2024 about 880 earthquakes with magnitudes greater than 3.5 occurred in Western region of Mongolia. This represents approximately 20% of all earthquakes with magnitudes greater than 3.5 that occurred in Mongolia (*See Graph 2 and Fig 2*).



Graphic 2. Magnitude distribution of earthquakes in the western region of Mongolia from 1964 to 2024

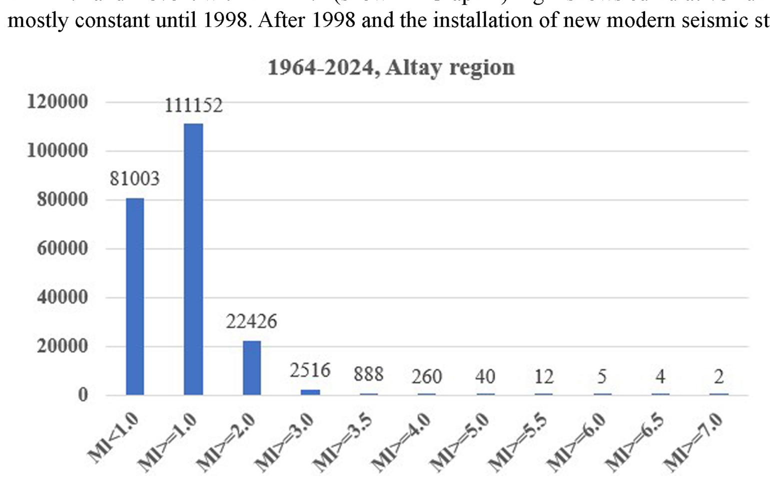
RESULTS and DISCUSSION

a. Study of seismic regime around western region (Altay region)

Altay region of Mongolia is one seismic active areas and have a lot of faults created by strong earthquake.

From 1964 to 2024, Mongolia seismic network stations recorded more than 167063 earthquakes with magnitude from 0.5 to 7.3 in western region.

At this time, around 111152 events with M>1, 22426 events with M>=2.0, 2516 events with M>=3.0, 260 events with Ml>=4.0, 40 events with Ml>=5.0, 5 events with Ml>=6.0 and 2 event with Ml>=7.0 (shown in Graph 3) Fig 4 shows cumulative number of detected events with time in Altay region. Annual number of events in Altay is mostly constant until 1998. After 1998 and the installation of new modern seismic stations, we could increase the number of detected events.



Graphic 2. Magnitude distribution of earthquakes in the western region of Mongolia from 1964 to 2024

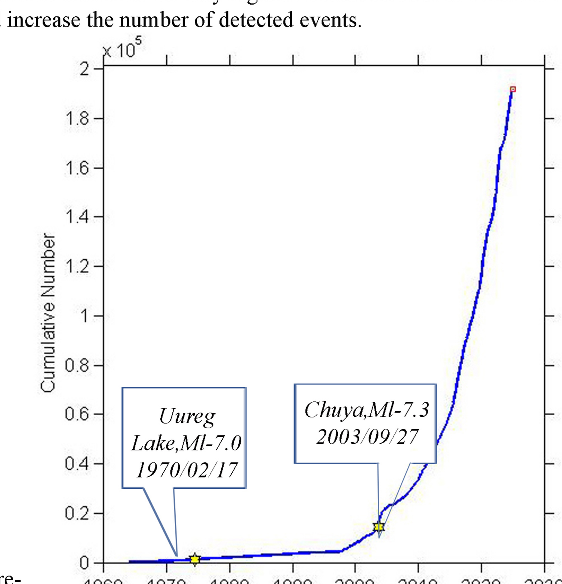


Fig 4. Cumulative number of detected events with time in western region

Fig 6. shows magnitude-frequency relation. We used all data with magnitude more than 1.0 recorded between 1964 and 2024. Magnitude interval was choose as Md=0.1. Data completeness is at magnitude Mc = 1.4. At the scale of whole Mongolia, we estimated a rather low b = 0.758 value and high seismic activity a = 5.86. This low b value shows the frequently occurrence of large earthquakes in Mongolia, even since 1964

Estimated by IAG, in Altay region, from 1964 to 2002, a=5.2 and b=0.7 for magnitudes M>=2.0 [8].

This shows that Altay zone is associated with high seismic activity and is the place of frequently big earthquakes.

Also, we estimated a and b value different seismic active faults in west part of Mongolia. These zones are characterized by very high seismic activity. Examples,

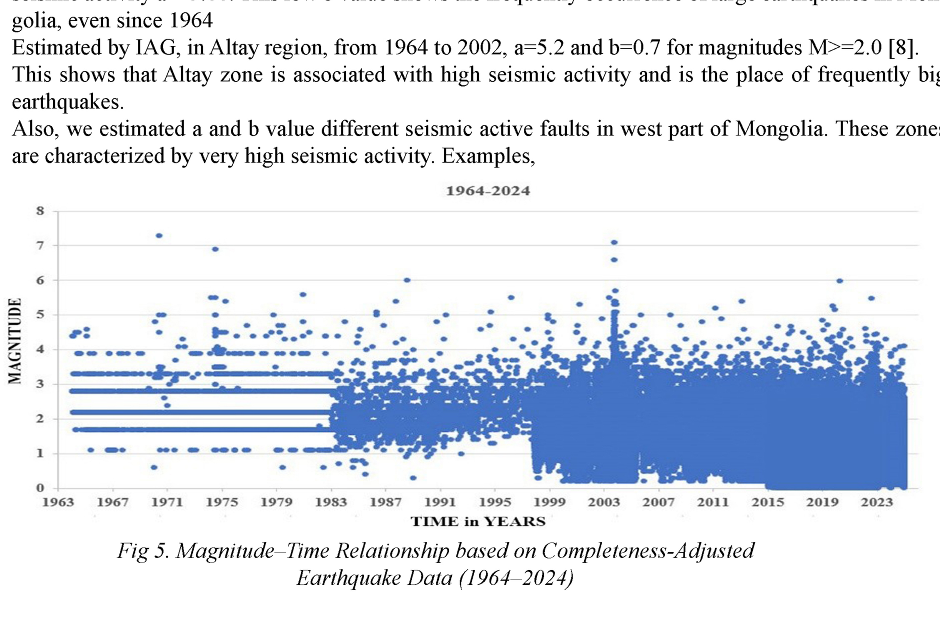
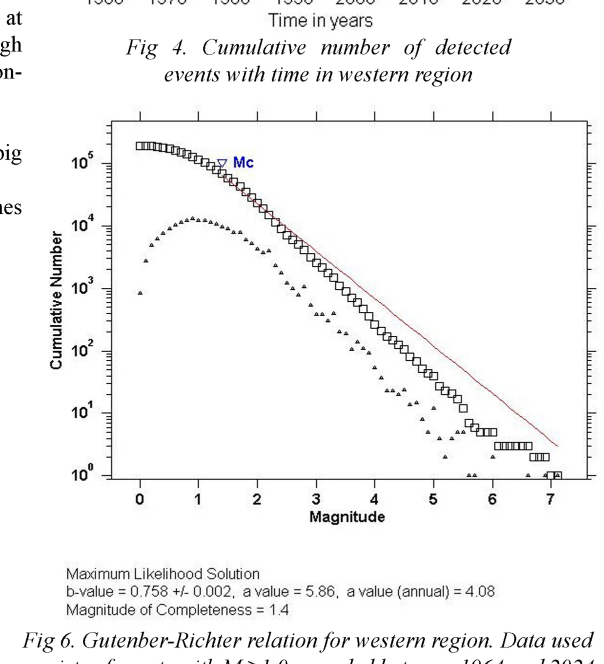


Fig 5. Magnitude–Time Relationship based on Completeness-Adjusted Earthquake Data (1964–2024)



Maximum Likelihood Solution
b-value = 0.758 +/- 0.002, a value = 5.86, a value (annual) = 4.08
Magnitude of Completeness = 1.4

Fig 6. Gutenber-Richter relation for western region. Data used consists of events with M ≥1.0 recorded between 1964 and 2024.

b. Results of the Analysis of the Poisson Distribution and Seismic Probability

$$P(k) = e^{-\frac{events}{time}period} \cdot \frac{(\frac{events}{time}period)^k}{k!} \quad (3)$$

$$\frac{events}{time} * time\ period = \lambda \text{ then } P(k) = e^{-\lambda} * \frac{\lambda^k}{k!} \quad (4)$$

The Poisson distribution was applied to estimate the probability of earthquake occurrences per year.

The Poisson distribution was adapted for use in calculating the probability of earthquake recurrence. Since 1998, based on 27 years of data, the probability of a strong earthquake in a year was calculated using the Poisson distribution (see table 1). Before that, I learned to explain how the logarithmic value of the annual average number of earthquakes depends on the magnitude using the Gutenberg-Richter law. After 1998, taking into account the conditions that made it possible to fully record strong earthquakes with a magnitude greater than 0.5, the following results were obtained.

from Fig 7, the earthquake recurrence b-value=0.886, degree of earthquake activity a=4.4 and coefficient of determination R2=0.9898. This high R² value (0.9898) indicates a strong linear correlation, which is consistent with the Gutenberg–Richter law. The slope of the regression line (b-value ≈ 0.89) suggests a relatively frequent occurrence of large-magnitude earthquakes in the region.

Based on the above results, the Poisson distribution was calculated using data on earthquakes with magnitudes of 5.0 or greater that occurred during the periods 1964–2024 and 1998–2024 (see table 3).

First, we have shown Probability of no earthquake (Ml>=5.0) occurring during 1 year. For shown Table 2, since there were 40 earthquakes over 60 years, the average yearly rate is:

$$\lambda = \frac{40}{60} = 0.6667 \text{ then } P(0) = e^{-\lambda} = e^{-0.6667} = 0.5134$$

The probability that no earthquake occurs during 1 year is approximately 51.34%.

The probability of at least one earthquake occurring in 1 year is given by:

$$P(\geq 1) = 1 - P(0) \quad \text{then} \quad P(\geq 1) = 1 - 0.5134 = 0.4866$$

The probability of an earthquake occurring in 1 year is approximately 48.66%.

Second, let us calculate the probability of no earthquake occurring during a 5-year period.

40 earthquakes occurred Ml>=5.0 over 60 years:

$$\lambda = \frac{40}{60} = 0.6667 \text{ then}$$

Average number of earthquakes over 5 years:

$$\lambda = 5 \times 0.6667 = 3.3335$$

Using the Poisson distribution:

$$P(0) = e^{-\lambda} = e^{-3.3335} = 0.0358$$

The probability of no earthquake occurring during a 5-year period is approximately 3.58%.

Probability of at least one earthquake occurring during a 5-year period:

$$P(\geq 1) = 1 - P(0) = 1 - 0.0358 = 0.9642$$

The probability of an earthquake occurring over 5 years is approximately 96.42%.

M>=	Events	time	average event	LogN
0.5	162470	27	6017.407	3.779
1.0	106581	27	3947.444	3.596
1.5	52478	27	1943.630	3.289
2.0	19392	27	718.222	2.856
2.5	5648	27	209.185	2.321
3.0	1963	27	72.704	1.862
3.5	657	27	24.333	1.386
4.0	172	27	6.370	0.804
4.5	61	27	2.259	0.354
5.0	22	27	0.815	-0.089
5.5	5	27	0.185	-0.732
6.0	2	27	0.074	-1.130
6.5	2	27	0.074	-1.130
7.0	1	27	0.037	-1.431

Table 2. The methodology used to calculate the data for the period 1998–2024

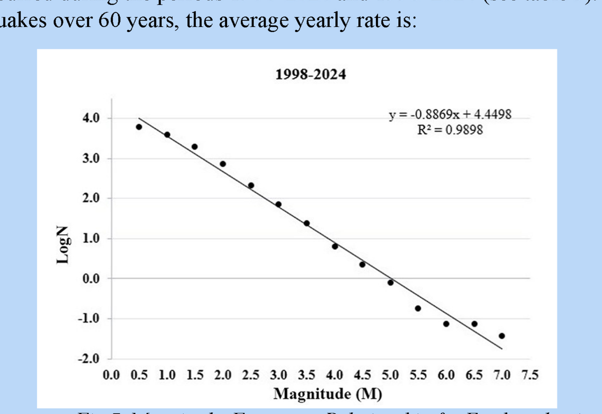


Fig 7. Magnitude–Frequency Relationship for Earthquakes in Western Mongolia over a 27-year period (Gutenberg–Richter law, 1998–2024, Mc = 0.5)

For the period from 1964 to 2024, the annual occurrence rates of earthquakes with magnitudes greater than 5.0 were calculated for both 60-year and 27-year intervals. Using the Poisson distribution functions (Equations 3 and 4), the probability of observing k earthquakes with magnitudes greater than 5.0 in a single year was estimated (Table 3, Fig 8).

Calculated Poisson Distribution for the Periods 1964–2024 and 1998–2024 (Ml ≥ 5.0)

Time period	1 year		2 year		3 year		4 year		5 year	
Probability	λ=0.66 (60 years)	λ=0.81 (27 years)	λ=0.66 (60 years)	λ=0.81 (27 years)	λ=0.66 (60 years)	λ=0.81 (27 years)	λ=0.66 (60 years)	λ=0.81 (27 years)	λ=0.66 (60 years)	λ=0.81 (27 years)
P(k=0)	51.3	44.3	51.3	44.3	51.3	44.3	51.3	44.3	51.3	44.3
P(k>=1)	48.7	55.7	48.7	55.7	48.7	55.7	48.7	55.7	48.7	55.7
P(k=1)	34.23	36.07	35.15	31.94	27.07	21.21	18.53	12.52	11.89	6.93
P(k=2)	11.41	14.70	23.43	26.03	27.07	25.93	24.71	20.40	19.82	14.11
P(k=3)	2.54	3.99	10.41	14.14	18.04	21.12	21.96	22.17	22.02	19.17
P(k=4)	0.42	0.81	3.47	5.76	9.02	12.91	14.64	18.06	18.35	19.52
P(k=5)	0.06	0.13	0.93	1.88	3.61	6.31	7.81	11.77	12.23	15.91

Table 3. Calculated Poisson distribution 40 events for 60 years and 22 events for 27 years in Ml>=5.0

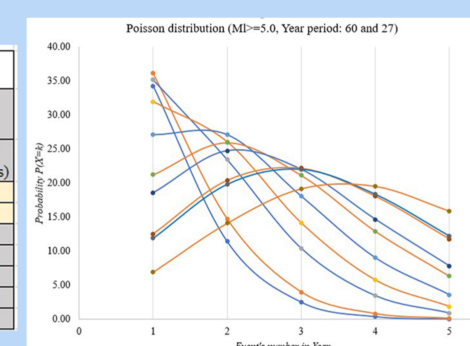


Fig 8. Seismic Probability Estimation based on the Poisson Distribution (Ml>=5.0, period of Years: 60 and 27)

According to the results based on the Poisson distribution, during the periods of 60 years (1964–2024) and 27 years (1998–2024), the probability of earthquakes with a magnitude of ≥5.0 occurring once or twice per year is the highest. The figure shows Poisson probability distributions modeling the annual occurrence of earthquakes with magnitude M≥5.0, based on datasets spanning 27 and 60 years. The peaks of the curves shift depending on the average event rate (λ), indicating that lower λ values favor a higher probability of one event per year, while higher λ values shift the peak toward multiple events per year. This demonstrates the suitability of the Poisson model in estimating the likelihood of earthquake occurrence frequencies over time. In Table 3 and Fig 8, it was found that there is a 0.34 probability that an earthquake with magnitude greater than 5.0 will occur more than once in 1 year, and a 0.11 probability that it will occur more than twice in 1 year.

CONCLUSION

In this study, the seismic characteristics of the mountainous Altai region in western Mongolia were investigated to assess the current state of seismic activity, the frequency of earthquake recurrence, and the level of seismic hazard in the region. The research was conducted using earthquake data from the National Data Center of the Institute of Astronomy and Geophysics, Mongolian Academy of Sciences. The dataset includes historical moderate-to-strong earthquakes that occurred between 1900 and 1963, as well as instrumental data from 1964 to 2024 for earthquakes with magnitudes greater than 0.5.

1. Seismic activity and recurrence patterns in the region were analyzed. The key parameters describing the seismic behavior — the a and b values — were estimated using the Gutenberg–Richter law. Additionally, the statistical probability of earthquake occurrence over 60-year and 27-year periods was calculated using the Poisson distribution.
2. From 1964 to 2024, Mongolia seismic network stations recorded more than 167063 earthquakes with magnitude from 0.5 to 7.3 in western region. At this time, around 111152 events with M>1, 22426 events with M>=2.0, 2516 events with M>=3.0, 260 events with Ml>=4.0, 40 events with Ml>=5.0, 5 events with Ml>=6.0 and 2 event with Ml>=7.0 (shown in Graph 3).
3. In Fig 6 shows magnitude-frequency relation. We used all data with magnitude more than 1.0 recorded between 1964 and 2024. Magnitude interval was choose as Md=0.1. Data completeness is at magnitude Mc = 1.4. At the scale of whole Mongolia, we estimated a rather low b=0.758 value and high seismic activity a=5.86. This low b value shows the frequently occurrence of large earthquakes in Mongolia, even since 1964. According to estimates by the Institute of Astronomy and Geophysics (IAG), in the Altay region from 1964 to 2002, the Gutenberg–Richter parameters were a = 5.2 and b = 0.7 for magnitudes M ≥ 2.0 [8]. These results show that the b-value remained approximately the same, while the seismic activity slightly increased, as indicated by the higher a-value.

Based on Poisson distribution modeling using earthquake data from the periods 1964–2024 (60 years) and 1998–2024 (27 years), the expected annual frequency of earthquakes with magnitude ≥5.0 is estimated to be λ = 0.66 and λ = 0.81, respectively. The shorter, more recent period reflects a higher seismic activity rate. The probability of no earthquake occurring (P=0) decreases significantly with longer time intervals, while the probabilities of multiple events (P≥ 2) increase accordingly. For instance, over a 5-year period, the probability of three or more earthquakes reaches over 40% for λ = 0.81. In contrast, the chance of zero earthquakes over the same period drops to approximately 11–17%. This analysis demonstrates that recent decades have shown increased seismic activity in the region, and the Poisson model effectively captures the statistical likelihood of earthquake occurrences across various time spans. These results are important for seismic hazard assessments, infrastructure planning, and preparedness in western Mongolia and similar seismically active regions.

In the future, the seismic situation in the western region can be studied in connection with seismic activity along active faults, which may provide an opportunity to forecast the probability of strong earthquakes.

Sample list of References

1. Andrzej Kijko, e. a. Estimation of the Frequency–Magnitude Gutenberg-Richter b-value without making Assumptions on levels of Completeness, 2017
2. Baasanbat Ts, Seismic Observation Network and Seismicity of Mongolia, 2013
3. Baljinnyam, I., A. Bayasgalan, B.A. Borisov, A. Cisternas, M.G. Dem'yanovich, L. Ganbaatar, V.M. Kochetkov, R.A. Kurushin, P. Molnar, H. Philip, and Y.Y. Vashchilov, Ruptures of Major Earthquakes and Active Deformation in Mongo-lia and its Surroundings. Vol. Memoir 181 of Boulder, Colorado: The Geological Society of America, Inc., 1993. 64.
4. Felzer, K. R Calculating the Gutenberg-Richter b value, 2006
5. Haight, Frank A. (1967). Handbook of the Poisson Distribution. New York, NY, US: John Wiley & Sons. ISBN 978-0-471-33932-8.
6. Хилько, С.Д. Землетрясения и основы сейсмического районирования Монголии. Москва, "НАУКА". 1985
7. Leskova E.V, E. A. (2007). THE CHUYA EARTHQUAKE. Conference commemorating the 50th anniversary of the 1957 GOBI-ALTAY eartthquake, (p. 102). Ulaanbaatar, Mongolia.
8. Ulziibat M. The 2003 Chuya sequence (North Altay range): tectonic context and seismological sudy. 2006, France