Spatiotemporal Distribution of Strong Earthquakes and the Time Course of the Parameters of the Seismic Regime of the Bishkek Seismic Research Site of Kyrgyzstan

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Abstract
This paper analyzes spatiotemporal distribution of strong historical earthquakes within the Bishkek seismic research (BSR) site. The main focus is on the spatial and temporal characteristics of crustal earthquakes in the instrumental period of observation, particularly the last 30 years (1991-2020). This period was the time of transition from the analog earthquake recording system to a digital one. Available epicenter maps of weak to moderate earthquakes were analyzed to identify areas of high and low seismic density. The analysis uses such parameters as the total number of earthquakes, magnitude, slope of the recurrence curve, and total seismic energy. The time course of seismic parameters was the main factor used to assess the current seismic setting of the Bishkek seismic research site. The slope of the earthquake recurrence curve was calculated using two methods: the least squares method and the maximum likelihood method. The analysis identified a downward trend showing a decrease in the number of earthquakes in the past 30 years (1991-2020). The results of this research can help develop a methodology for strong earthquake prediction and seismic hazard assessment of the BSR area.

1. Introduction

The seismic setting of an area is characterized by the cumulative number of earthquakes that have occurred in that area over a certain period of time (Riznichenko, 1985). The Bishkek seismic research site is located in the highly active North Tien Shan seismic zone. In the past 135 years (1885-2020), the study area and its immediate surroundings witnessed a number of catastrophic seismic events, such as the 1885 Belovodsk earthquake (M=6.9±0.5), the 1887 Vernensk earthquake (M=7.3±0.5), the 1911 Kemin earthquake (M=8.2±0.5), the 1889 Chilik earthquake (M=8.3±0.5), the 1938 Kemin-Chui earthquake (M=6.9±0.5), and the 1992 Suusamyr earthquake (M =7.3±0.3), as well as a range of weaker earthquakes. These earthquakes caused enormous economic damage and claimed thousands of human lives. This is why seismic research and seismic hazard assessment of Kyrgyzstan and adjacent areas remain highly relevant today. The main source parameters of an earthquake are geographical coordinates of its epicenter (φ^0N and λ^0E), time of its occurrence (t), depth of its hypocenter (h, km), and its energy class (K_R) (or magnitude (M)).

The source parameters of known strong historical earthquakes in the region were determined from available macro-seismic data for the period since 1770 (Januzakov et al., 1977). The Institute of Seismology at the National Academy of Sciences of the Kyrgyz Republic compiled a catalog of earthquakes with energy class of 10 and higher (K≥ 10) using instrumental seismic data since 1955. In recent years, the earthquake catalogs of Kyrgyzstan (including for BSR) have been updated with new computations of earthquake source parameters from digital earthquake records. Detailed seismic analysis of the Frunze (Bishkek) research site (BRS) began in 1975 (Grin et al., 1976). Back then, data came from a temporary field-based seismic monitoring network around BRS and the regional network of analog seismic stations. In recent years, this regional network has been fully re-equipped with digital seismic stations.

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A local KNET digital seismic network was deployed at BRS in 1991 as per the Kyrgyzstan's Seismic Monitoring Development Framework (Muraliev,1993 and Vernon, 1992).

This KNET telemetry network is unique for the Central Asian region and has helped collect many unique digital records of earthquakes in the past thirty years. The source parameters of local earthquakes were determined by processing a large amount of data from regional seismic stations. Data processing was performed by the data center of the Institute of Seismology at the NAS of the Kyrgyz Republic using dedicated computer software. The accuracy of earthquake localization at BSR varies from 500 meters to 1-3 km. This work helped improve BRS earthquake catalog compilation processes. The above necessitated the need for detailed analysis of BRS seismic setting using digital data from the past 30 years (1991-2020).

The purpose of this work is to identify the spatio-temporal features of the distribution of historically strong earthquakes and to study the temporal course of the parameters of the seismic regime in order to obtain a general idea of the current state of the seismic regime of the Bishkek prognostic polygon. The following objectives were identified to achieve this goal: to analyze available earthquake catalogs; to study spatial and temporal distribution of strong BRS earthquakes; to compute numerical values of key earthquake parameters (number of earthquakes, N; seismicity rate, A_{10}; slope of the earthquake recurrence curve and other); to build time series graphs of these parameters for the period of 1991-2020; and to analyze their spatiotemporal characteristics.

2. Methodology and Source Data

The seismic setting of the Bishkek research site was evaluated using quantitative methods of seismic analysis (Methods of Detailed Seismic Analysis, 1960). The slope of the earthquake recurrence curve was computed using the least-squares and maximum likelihood methods. The first method (graphical) plots the correlation between the number of earthquakes and their energy classes, $N = N(K_R)$. The second method, the maximum likelihood method, calculates the γ value using the formula below (Culldorf, 1966):

$$\gamma = \log\left[1 + \frac{N_\Sigma}{\sum_{0}^{\infty} j \cdot n_{K_0+j}}\right]$$

Equation 1

including dispersion assessment $\sigma = \frac{\gamma}{\sqrt{N_\Sigma}}$, where N_Σ is the total number of earthquakes, n_{K_0+j} – is the number of earthquakes with energy class of K_{0+j}; and K_0 is the representative energy class (K_0=7). Energy class to magnitude (M) of conversion is done using the following formula (Rautian, 19600):

$$M = \frac{K_R - 4}{1.8}$$

Equation 2

Where K_R is energy class; hence, seismic energy is $E_S=10^{K_R}$[J]. Bulk data processing of each earthquake included determinations of their main parameters as well as their energy classes (K_R) and different magnitude types (M_{LH}, M_S, M_{pv}, etc.). Magnitude M in the formula above (2) is M_{LH}, which is based on the maximum amplitude of surface waves. Working with different earthquake catalogs often requires the conversion of energy classes K_R to magnitudes M and vice versa. This can be accomplished using the formula above (2). For catastrophic earthquakes with magnitude of ≥7, it is better to use moment magnitude M_W, which is derived from scalar seismic moment M_0 (Hanks and Kanamory, 1979).

Seismicity: The geographic coordinates of BRS are 41.8°-43.5° N latitude and 74°-79° E longitude. The research site now extends further eastwards as compared to previous years (Grin et al., 1974) and includes the Chui and Issyk-Kul valleys with surrounding mountains (Figure 1). Geological and geophysical settings of the study area are described in a number of papers (Grin et al., 1974 and Januzakov et al., 1977). For seismicity analysis, an earthquake epicenter map was built using 94 strong (K_R≥12) historical earthquakes (Figure 1) from ancient times to 2020. Strong earthquakes were selected from the catalog (Seismological Data, 1982), including recent seismic events with energy classes of K_R≥12. Figure 1 shows that the majority of strong earthquake epicenters are concentrated along the Kyrgyz, Kungey Ala-Too and Trans-Ili Alatau Ranges, comprising the North Tien-Shan seismic zone. Earthquakes in the southern part of the study area have significantly smaller magnitudes as compared to the earthquakes in the north. In addition, the map shows that strong earthquakes tend to recur at the same locations once in about a hundred years. This is such a crude assumption.

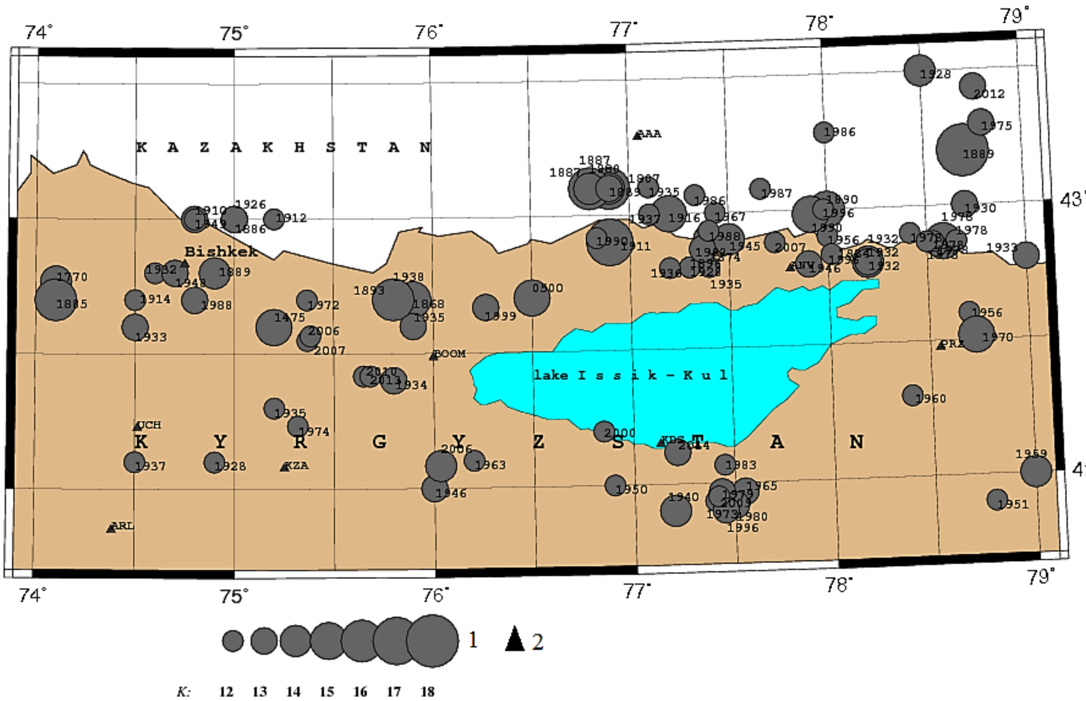

Figure 1: Strong earthquake epicenters within the Bishkek research site. Legend: 1 – earthquake epicenters with years; 2 – seismic stations with abbreviated names

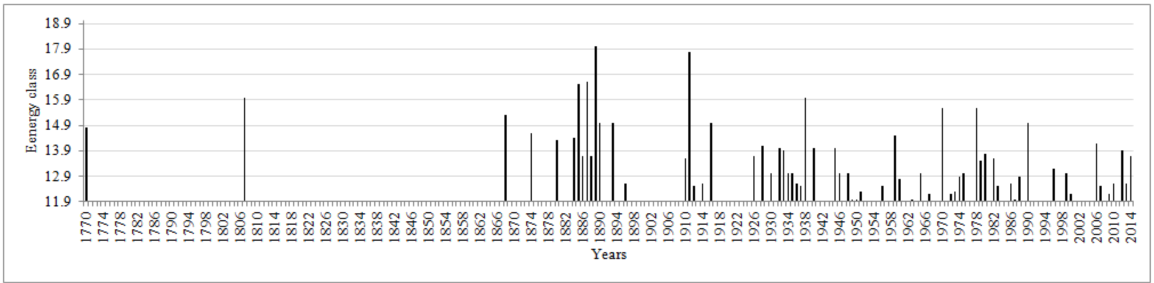

Figure 2: Temporal distribution of strong ($K_R \geq 12$) BRS earthquakes

For example, an 8-intensity earthquake near Belovodskoye Village in 1770 was followed by a 9-10 intensity earthquake in the same area in 1885. The time span between these two seismic events is 115 years. Another example is the 8-9 intensity Kemin-Chui earthquake in 1938, which was preceded by an 8-intensity earthquake in 1868, i.e. 70 years earlier, and other(see Figure 1).

The key seismic characteristic of the Bishkek research site is that it is prone to strong earthquakes, such as the 10-11-intensity Kemin earthquake (1911), 10-intensity Chilik earthquake (1889), 8-9-intensity Kemin-Chui earthquake (1938), 8-intensity Sarykamysh earthquake (1970), and other 6-7-intensity earthquakes (Figure 1) with hypocenter depths of 5 to 35 km (Januzakov et al., 1977) that are the key components of the North Tien-Shan seismic zone. The North Tien-Shan seismic zone is characterized by moderate seismicity (A_{10}=0.11-0.15), earthquake recurrence slope γ of 0.48, maximum observed magnitude of 8.4, maximum predicted magnitude of 8.1, and recent tectonic deformation of $(5\text{-}6)\cdot 10^{-7}$ year^{-1}(Yudakhin, 1983).

Figure 2 shows the distribution of strong ($K_R \geq 12$) BRS earthquakes over time. The figure spans the time period from 1770 to 2014 and covers 94 seismic events. It should be noted that there were no earthquakes with energy class of $K_R \geq 12$ between 2014 and 2020. This is why Figure 2 shows earthquakes until 2014 only. Changes in the seismic activity over time become noticeable after 1868. The 1889 Chilik earthquake (K_R=18) falls into a period of higher seismic activity, which lasted for 29 years (from 1868 to 1896). A 13-years period of seismic quiescence started in 1897 and ended in 1909. The notoriously known 1911 Kemin earthquake (K_R=17.8) happened during a 7-year period of higher seismic activity (between 1910 and 1916). This seismically active period was followed by 9 years of seismic quiescence (from 1917 to 1925). The 1938 Kemin-Chui earthquake (K_R=16) occurred during another 26-year-long period of seismic activity (from 1926 to 1951), etc. Strong earthquakes are clearly recurrent: years of seismic quiescence alternate with periods of higher seismic activity and vice versa, but the duration of these periods is different. Strong earthquake recurrence times in the Tien-Shan region are considered in paper (Mamyrov, 2012). A more detailed study is needed to better understand the recurrence patterns of high seismic activity. Such a study was carried out by the authors and published in (Sabirova and Muraliev, 2017). The Chui, South Issyk-Kul and Kungey seismic zones have the highest concentrations of earthquake epicenters. Areas with the highest concentrations should be considered as zones of high seismic hazard prone to earthquakes in future.

Figure 3 shows the temporal distribution of representative BRS earthquakes (K_R=7-14) between 1991 and 2020. Analysis shows that the total number of earthquakes has decreased in the past thirty years (Figure 3), from 260 seismic events to 31. Such a decrease in the number of relatively weak earthquakes might be indicative of a major seismic event in future. This should be the subject of further research in strong earthquake prediction. Figure 4 shows the distribution of representative BRS earthquakes by energy class. The figure demonstrates that the majority of BRS earthquakes have energy class of 7. This follows from the linear law below:

$$lgN=6.79 - 0.48\ K_R \qquad \text{Equation 3}$$

Where K_R is the energy class and N is the number of earthquakes. The slope of the earthquake recurrence curve γ was found to be -0.48. The recurrence curve was built using 3,935 seismic events with energy classes of 7 to 14. Earthquakes with energy class of 11 happen annually once or two times a year. The intensity of an earthquake with a hypocenter depth of 5-10 km measures up to 4. Earthquakes with energy class of 10 happen three times a year while earthquakes with energy class of 8 occur on a monthly basis.

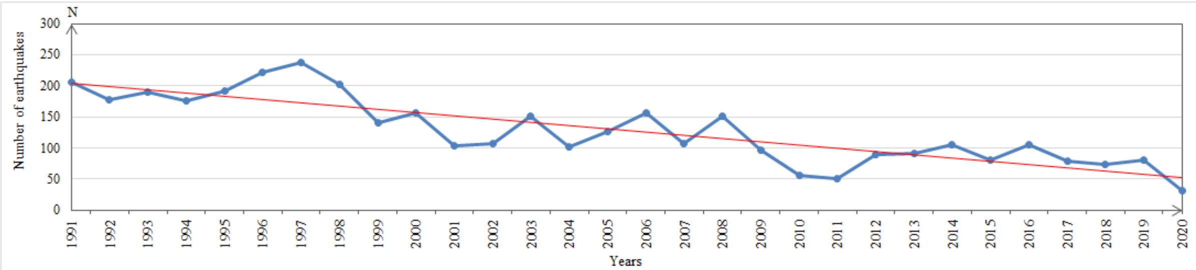

Figure 3: Time course of the number of earthquakes of BRS in time

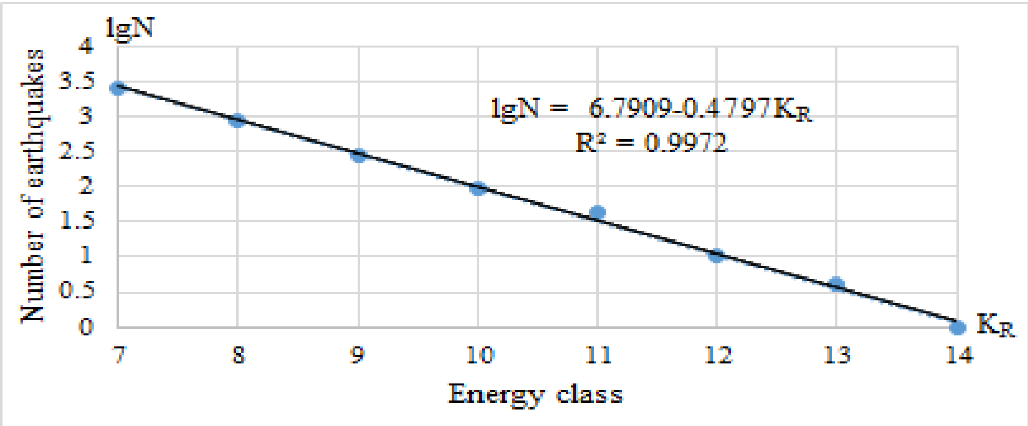

Figure 4: BRS earthquake recurrence curve: correlation between the number of earthquakes (N) and their energy classes (K_R)

Seismic activity or seismicity is the average number of earthquakes of a certain energy class (magnitude) that happen over a period of time in a certain area (Riznuchenko, 1985). The A_{10} seismicity rate is widely used today in seismic analysis as earthquakes with energy class of 10 and above informative among other representative seismic events with energy class of $K_R \geq K_{min}$. They are easily captured by both regional and local seismic networks. The A_{10} seismicity rate was calculated for BRS using the formula below (Riznichenko, 1985):

$$A_{10} = \frac{(1-10^{-\gamma})}{10^{-\gamma(K_{\min}-10)}} \cdot \frac{1000 N_{\Sigma}}{\Delta S T},$$

Equation 4

where N_{Σ} is the total number of BRS earthquakes with energy class of $\geq K_{min}$; ΔS is the size of the research site (sq. km); T is the time of observation, year; and γ is the slope of the earthquake recurrence curve. Computation results are presented below as a time series graph (Figure 5). The A_{10} seismicity rate varies from 0.12 to 0.01. This is a relatively low value as compared to other seismically active areas in Kyrgyzstan (Sabirova and Muraliev, 2017). Higher seismic activity was reported in 1996, 2006, 2014 and other years of strong and sensible earthquakes. The time curve of the A_{10} seismicity rate is relatively complex. However, Figure 6 demonstrates a decrease in seismic activity in the past 30 years (1991–2020).

The BRS *earthquake recurrence curve* $N=N(K_R)$ is shown in Figure 5. Figure 5 shows that the earthquake recurrence curve BRS has a linear in the range of energy classes from 7 to 14 for the period from 1991 to 2020. The slope of the recurrence curve γ is -0.48. The γ-value was calculated using the least-squares smoothing method, $N=N(K_R)$, and also the maximum likelihood method (1). Annual γ-values from the formula above (1) are presented in Figure 6. The figure shows γ-values with dispersion ($\pm\sigma$). The γ-value was calculated using a total of 3,935 earthquakes with energy classes ranging from 7 to 14 that have occurred in the study area over the past 30 years (1991–2020). Figure 6 shows that γ-value vary from 0.59 to 0.29. The long-term average slope of the earthquake recurrence curve is 0.48. The γ-value has decreased in recent years to 0.35 (Figure 6). Comparison analysis shows that both methods give similar results for the γ-value.

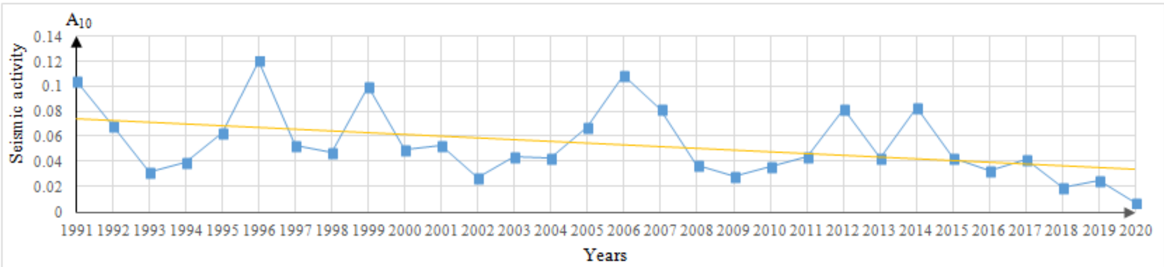

Figure 5: Time course of parameterA_{10} of BRS

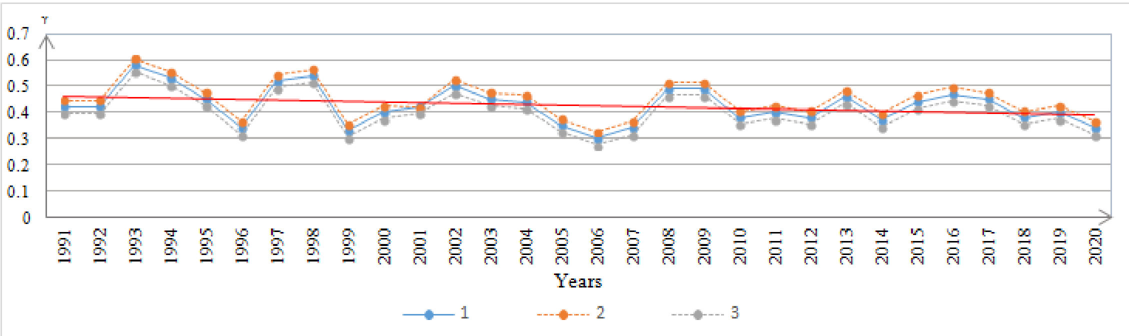

Figure 6: Time course of parameter γ-values of BRS

3. Discussion

Analysis of spatiotemporal distribution of crustal earthquakes provided a deeper insight into the seismic setting of the Bishkek research site. The epicenters of strong (K_R=12-18) earthquakes are non-uniformly distributed in the study area (Figure 1), concentrating mainly in the North Tien-Shan and South Issyk-Kul seismic zones. The majority of strong earthquake epicenters are located in the

Kungey, South Issyk-Kul, Chui and other seismic sub-zones (Figure 1). The epicenters of catastrophic earthquakes with magnitude of over 8, namely the 10-11-intensity Kemin earthquake (1911) and 10-intensity Chilik earthquake (1889), are located in the highly seismically active Kungey zone. It has been 110 years since the 1911 Kemin earthquake and 132 years since the 1889 Chilik earthquake. Assuming that strong earthquakes happen at the same locations every 100 years, a strong earthquake can be expected in near future. On the other hand, the overall seismicity of the study area has decreased after those catastrophic events. Earthquakes with energy class of ≥12 are not common in the study area as compared to other seismically active regions of Kyrgyzstan. The BRS seismic analysis is based mostly on weak earthquakes (K_R=7-11). It should be noted that the epicentral areas of strong, moderate and weak earthquakes are nearly coincident. This may mean that strong earthquakes are preceded by not only moderate, but also weak seismic events. This is why it is important to study how the seismic setting of an area changes over time.

Time series graphs were built for the γ (Figure 6) and A_{10} (Figure 5) values. The γ-value was calculated using two non-related methods: the least-squares method and the maximum likelihood method. The resulting γ-values were found to be very similar (see Figure 6). However, both γ and A_{10} values change over time. Time variations of the γ-value before strong earthquakes were first discussed in paper (Mamadaliev, 1964). Variations of the γ-value, seismotectonic strain and stress in Southwest Kyrgyzstan are analyzed in paper (Muraliev, 1989). Time series graphs of the BRS seismic setting show a decrease in seismic activity (Figures 3, 5 and 6). This can be either precursor of a strong seismic event or simply an indication of decreasing seismicity in the last 30 years (1991–2020).

4. Conclusion

The space-time distribution of strong earthquakes in the BRS has the following features:

1. The epicenters of strong earthquakes form a narrow zone and reflect the high seismicity of the North Tien Shan zone (Figure 1).
2. The zone of strong earthquake epicenters coincides with the axial part of the Kyrgyz ridge, the Kungei ridge and the Zailiyskiy Ala-Tau, which extend in a nearly latitudinal direction.
3. The epicenters of expected strong earthquakes are likely to be within this zone. The time variation of seismic setting parameters at BRS showed that:
    a. Seismic activity has been gradually decreasing in the last 30 years (1991– 2020). The average annual number of earthquakes with energy classes of 7 to 14 has dropped from 200 to 50.
    b. Time series graphs of parameters seismic regime (N, A_{10} and γ) show a decreasing trend in the past years.
    c. It should be noted that the analyzed variations of seismic parameters can be effectively used in further earthquake prediction and seismic hazard assessment studies.

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