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Earthquake recurrence time and patterns of forerunning earthquakes for selected subduction and collision zones

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Abstract. We analyze various data from selected subduction and collision zones, including Japan and Himalaya-Nepal regions. In the first case, we estimate the expected recurrence times of large earthquakes within a given magnitude range as functions of the Gutenberg-Richter's b values, for a given geodetic moment accumulation rate. It is argued, that the b value is related to rupture propagation conditions and asperity distribution, whereas the geodetic moment rate is controlled by the seismic moment budget derived from seismic and geodetic data. In the second case, we reveal the seismicity patterns and underlying asperity structures by using topological data analysis methods. In particular, we create graphs representing the forerunning earthquakes. We use the graph characteristics to distinguish among different seismicity patterns and scenarios. We argue that changes of these characteristics in time and space can be used for the task of seismicity forecasting.

Keywords: Earthquake forecasting, Gutenberg-Richter law, Recurrence time, Asperities, Forerunning earthquakes.

1 Introduction

Seismicity can be perceived as a stress accumulation-release process, in which the slow tectonic loading due to the relative plate movement is accommodated by alternating slow and fast slips along the plate interface. The asperity fault model describe the process [1,2]. It can also be described using statistics. To estimate the recurrence time of large earthquakes, we combine both views. Following the method proposed by Molnar [3] and applied to recent data by Avouac [4], we derive expression for earthquake recurrence times as a function of Gutenberg-Richter's b value. We obtain, however, more general expressions for the full range of b values, including $b \geq 1.5$. They enable us to estimate the recurrence times of earthquakes with magnitudes within a specific range Δm below the assumed maximum magnitude value, m_M, if the geodetic moment rate, $\dot{M}_G$, is given.

Two examples of the Nepal-Himalaya and Japan seismicity illustrate the proposed method of recurrence time and maximum magnitude estimation for a given region.

2 Methods

Recurrence time. The number of earthquakes with magnitudes greater or equal to m that occur in a given region and time period T is given by the Gutenberg-Richter law. It can be expressed as exponential pdf for magnitude,

$$p(m) = b' exp[-b'(m - m_T)]/(1 - exp[1 - b'(m_M - m_T)]) \quad (1)$$

where the magnitude range is $m \in \langle m_T, m_M \rangle$, and $b' = b \ln 10 = 1/\langle m_M - m_T \rangle$ defines the mean magnitude value [5]. For $b = 0$, the distribution is uniform,

$$p(m) = 1/(m_M - m_T). \quad (2)$$

The pdf can be expressed in terms of seismic moment, M_O, by using the expression

$$m = \log_{10}(M_O/10^{9.05})/1.5. \qquad (3)$$

Three different cases, $b = 0$, $b = 3/2$, and $b > 0, b \neq 3/2$, should be considered.

The number of all events, α, can be calculated from the expression

$$\alpha = \dot{M}_G \cdot T/\langle M_{SE}\rangle, \qquad (4)$$

where $\langle \mathrm{M_{SE}} \rangle$, is the mean seismic moment, calculated from the Gutenberg-Richter distribution expressed in terms of seismic moments, and M_G the geodetic moment accumulation rate that involves both the plate convergence rate, V_P, and aseismic slip rate, V_{AS}. In the long term, the geodetic moment is balanced by the seismic moment, $M_G = M_{SE}$.

The recurrence time of earthquakes from the seismic moment range $\langle \mathrm{M_O}, \mathrm{M_M} \rangle$ is

$$T_R = T/\left(\alpha \int_{\mathrm{M_O}}^{\mathrm{M_M}} p(M)dM\right), \qquad (5)$$

which gives

$$T_R = (M_M - M_T)/\ln(M_M/M_O)\,\dot{M}_G \quad \text{for } b = 0\ , \qquad (6)$$

$$T_R = \left(\frac{\beta}{1-\beta}\right)\left[\frac{M_M^{1-\beta} - M_T^{1-\beta}}{\left(M_O^{-\beta} - M_M^{-\beta}\right)\dot{M}_G}\right], \text{ for } b > 0 \text{ and } b \neq 3/2\ , \beta = 2b/3, \qquad (7)$$

and

$$T_R = \ln(M_M/M_T)\,/(M_O^{-1} - M_M^{-1})\dot{M}_G, \text{ for } b = 3/2. \qquad (8)$$

Equations (6-8) enable us to calculate the recurrence time of earthquakes with seismic moments greater or equal to M_O for the assumed threshold moment, M_T, maximum moment, M_M, b value, and the geodetic moment rate, $\dot{M}_G$, assumed to be released by earthquakes with seismic moments from the assumed range $\langle M_T, M_M \rangle$.

***b* value.** Earthquake rupture dynamics can be reflected by the scaling between the rupture area size and the slip deficit, $D_D = V_P T$, accumulated at a locked site,

$$A \propto {D_D}^{\gamma}. \qquad (9)$$

A low γ value means that lowered stress level and higher fault roughness prevent rupture front to propagate large distances between asperities. A high γ value means that due to growing slip deficit stronger and stronger asperities fail, causing slips over larger and larger areas. Higher γ are expected before large earthquakes since the stress grow in the region due to the locked asperity.

The Gutenberg Richter's b value can be related to γ as

$$b = 3/2(1 + \gamma). \qquad (10)$$

which provides the link between earthquake statistics and fault characteristics [5,6]. For instance, $\gamma \to 0$ and $b \to 1.5$ can be expected for the smallest and the largest earthquakes, where the source areas are defined by broken isolated asperities or barriers due to fault geometry or topography [6].

Maximum magnitude. Hierarchical asperity structure can be described by a forest graph of linked earthquakes. We define earthquake closeness, which depends both on the hypocentre distance and earthquake source sizes. Then, we define forerunner earthquakes. The pairs of close earthquakes such that the larger event follows the smaller one are selected, with the earliest larger one as the only parent, and the smaller as its child or forerunner. The latest and largest events without parents are roots of the trees and they can be identified with asperities. The forest consisting of disjoint trees reveals the asperity fault structure. By looking at distances between the neighboring roots, we estimate magnitudes of possible future earthquakes that connect different asperities and become new roots. Such an approach can be used to define the maximum magnitude needed for the recurrence time estimation.

3 Results

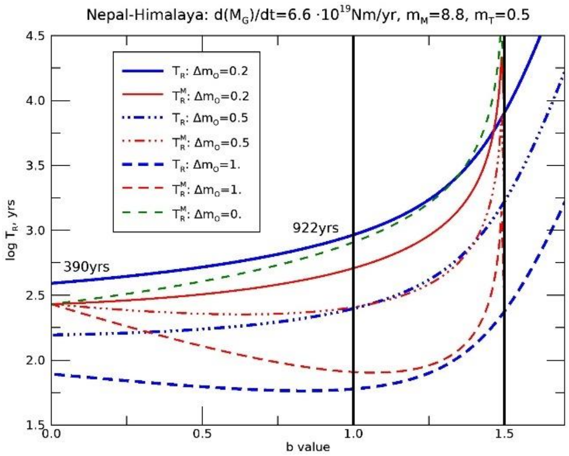

Fig. 1. Earthquake recurrence time as a function of b-value for the Nepal Himalayan region. We assume that m8.8 is the maximum magnitude in the region, so M_{MAX} =1.78 × 10^{22} Nm. The threshold magnitude m_T =0.5, and the moment deficit mean accumulation rate $\dot{M}_G$ = 6.6 × 10^{19} Nm/yr . The recurrence time depends on the magnitude interval $\Delta m = 0.2, 0{,}5,$ or 1 below M_{MAX}. Molnar's solutions, T_R^M, are shown for reference.

Nepal-Himalaya. The average convergence rate between the Indian and Eurasian tectonic plates along the 2,500-kilometer-long Himalayan arc is V_P = 20mm/yr. The convergence rate between India and South Tibet is 17.8mm/yr in central and eastern Nepal and 20.5mm/yr in western Nepal. The geodetic moment accumulation rate on the Main Himalayan Thrust 1,000-kilometer-long section underneath Nepal has been estimated as $\dot{M}_G$ = 6.6 × 10^{19} Nm/yr [8].

Recurrence times of large earthquakes are shown in Figure 1. For $b = 0$ we obtain T_R = 390, 156, and 78 yrs for respectively $\Delta m = 0.2, 0{,}5,$ and 1. For $b = 1$, T_R = 922, 249, and 60 yrs the same Δm values. b =1.5 seem unrealistic for full magnitude range. For Molnar's (1979) solutions, $T_R \to \infty$ for $b = 1.5$. Next we consider distribution of 1950-2023 $m \geq 4$ earthquakes along the Himalayan Arc from the USGS catalogue. Roots of related earthquake trees are shown in Figure 2. They can be thought of as representing isolated asperities. Magnitudes of

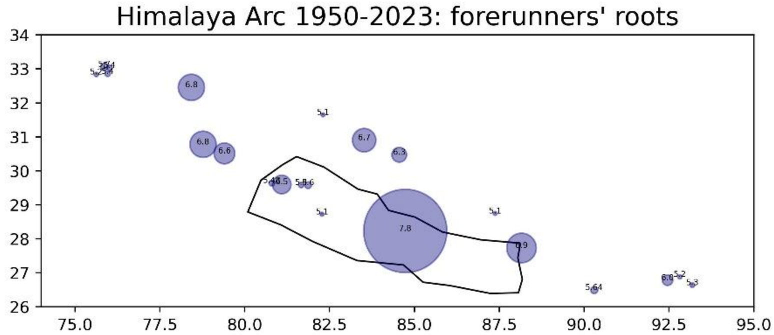

Fig. 2. Distribution of earthquakes 1950-2023 along Himalayan Arc. Roots of separated trees are shown only.

the future earthquakes that cover two isolated asperities can be calculated. For instance, the m8.8 earthquake is needed to break both asperities related m7.8 and m6.9 roots shown in Figure 2.

Honshu. The average convergence rate between the Pacific Plate and the North American Plate is V_P = 83mm/yr. The geodetic moment accumulation rate on the 1,000-kilometer-long section along Japan Trench has been estimated as $\dot{M}_G$ = 1.2 × 10^{20} Nm/yr [9].

Recurrence times of large earthquakes are shown in Figure 3. For $b = 0$ we obtain $T_R = 428$, 171, and 86 yrs for respectively $\Delta m = 0.2, 0{,}5,$ and 1. For $b = 1$, $T_R = 1010$, 273, and 67 yrs for the same Δm values. Results for b =1.5 seem unrealistic.

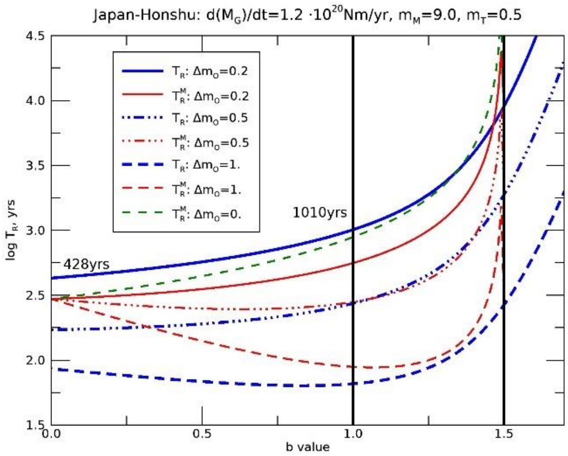

Fig. 3. Same as in Fig. 2. for Honshu region. We assume that m9 is the maximum magnitude in the region, so M_{MAX} =3.55 × 10^{22} Nm.

Next we consider distribution of 1950-2023 $m \geq 4$ earthquakes in the Honshu region from the USGS catalogue. We focus on distances between the forerunner roots just before the largest, 2011 Tohoku-oki m9 earthquake. For instance, m8.5 earthquake is needed to break both asperities related m7.7 and m7.5 roots, and m8.1 earthquake to break both asperities related m7.5 and m7.2 roots off the coast of Honshu shown in Figure 4.

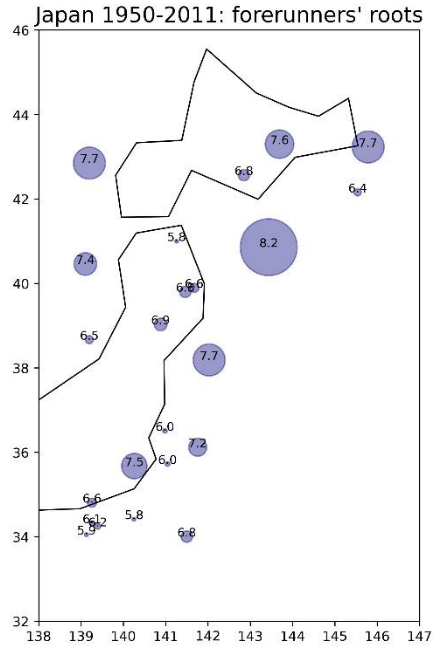

Fig. 4. Distribution of earthquakes 1950-2011, before the Tohoku-oki earthquake, along Japan Trench. Roots of separated trees are shown only.

4 Discussion

The asperity model assumes that the plate interface is divided into two interlocking parts, the high-coupled asperities and low-coupled non-asperity regions. Asperities break singly or in groups, depending on the stress level and fault roughness. They create also hierarchical structures, which suggests using their forest graph representation. The weaker asperities break singly first. After the last, strongest locked site fails, the weaker sites break again in larger events [2,7]. The largest m_M earthquake occurs in a given region, when all separated asperities break together.

The b value and the maximum magnitude, m_M, are considered within the asperity model context. The Gutenberg Richter's b value is related to fault characteristics, and it can depend both on time and magnitude range [5,6]. Here we assumed the same b value for the full magnitude range, but the method enables us divide the magnitude range into intervals with different b values. A more detailed analysis should take into account the proportion in which the accumulated moment deficit is released by the largest, moderate, and weak earthquakes.

5 Conclusions

Return times of strong earthquakes, estimated from the Gutenberg-Richter law, depend on three quantities:

- the rate of accumulation of geodetic moment related to the movement of tectonic plates;
- b value related to the slip propagation conditions along the contact of these plates;
- the magnitudes of the strongest possible earthquake in a given region.

Two examples of Nepal-Himalaya and Honshu coast regions show, how such estimates can be made from available geodetic data and earthquake catalogues.

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