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GEOLOGY

Estimation of Magnitudes of Old Earthquakes in the Gornyi Altai Region Based on Analysis of Seismogravitational Dislocations

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Estimation of the magnitudes of old earthquakes is a necessary condition for assessing seismic hazards and for seismotectonic zonation of active regions of the Earth. In this paper, we propose a new approach to the estimation of magnitudes of old earthquakes based on statistical analysis of landslide–slump (hereafter, seismogravitational) dislocations. This approach significantly extends the range of application of the paleoseismogeological method [1–3], which previously was based primarily on the study of fractures and the use of gravitational dislocations for establishing epicentral zones and the timing of old earthquakes.

By now, analysis of paleoseismotectonic dislocations has made it possible to define empirical relationships between different physical parameters of fractures and the magnitudes of responsible earthquakes [2, 3]. At the same time, the study of fractures has encountered several objective difficulties [3]: (1) subdivision of fractures caused by different paleoseismic events into age groups; (2) elucidation of the genesis and parameters of paleoseismic dislocations; and (3) elucidation of the genesis of neoseismic dislocations caused by the main shock, its aftershocks, or preseismic movements, which are essential for the determination of empirical relationships and subsequent estimation of the magnitudes of old earthquakes. The study of seismogravitational dislocations makes it possible to avoid such difficulties. However, establishment of the dependence of physical parameters of seismogravitational dislocations on the magnitude of earthquakes requires either statistical data on the major earthquakes and the consequent rockfalls, landslides, and so on (i.e., landslides in the broad sense) or detailed analysis of all landslides caused by one major seismic event. Statistical data of both types are absent for the majority of mountainous territories. In a recently published work [4], methods of statistical physics have been used successfully to determine the function of the statistical distribution of landslides for separate seismic events. These methods made it possible to calculate the dependence of different physical parameters of gravitational dislocations on the earthquake magnitude. For example, the relationship between the earthquake magnitude and the maximal volume of the related landslide is as follows [5]:

$$\log V_{L_{\max}} = 1.36M - 11.58 \pm \sigma, \quad \sigma = 0.49,$$

where $V_{L_{\max}}$ is the volume of the maximal landslide caused by the earthquake with magnitude M and σ is the standard deviation of the value.

Maximal (in volume) landslides are the most interesting objects for the paleoseismogeological method. First, they are retained in the relief for a longer time and, therefore, can be used for characterizing the duration of seismic activity. Second, each earthquake provokes several small landslides and only one maximal landslide. Thus, in contrast to fractures (in the broad sense), each large landslide characterizes an individual seismic event. Therefore, we can avoid the mandatory dating of all large landslides. Third, large landslides are best identified by the method of remote sensing. This is rather important because of the low accessibility of some mountain regions.

The topography of mountains in the Russian part of Altai (Gornyi Altai) has retained numerous traces of strong earthquakes as voluminous seismic rockfalls and landslides of the Holocene time. The Gornyi Altai region represents a northern extension of structures of the Mongolian and Gobi Altai, which are characterized by a high seismic activity recorded in the past as well. Nevertheless, it is only in the latest 1990s that the concept of low seismicity in this region was revised on the basis of the similarity of seismotectonic conditions in the Gornyi and Mongolian Altai regions [6].

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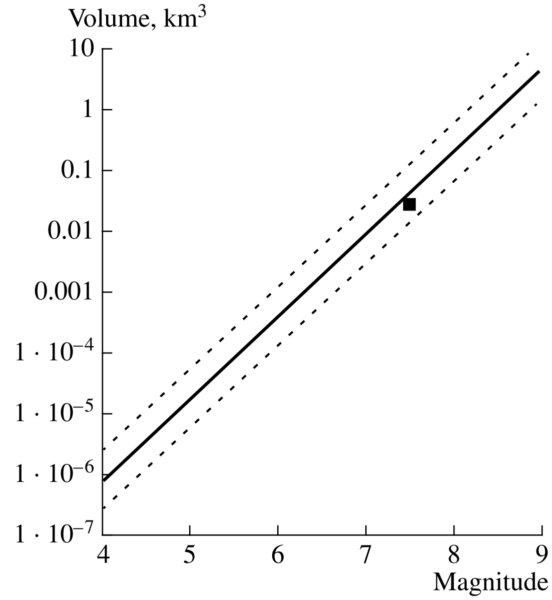
Using data on the Chuya earthquake in 2003 and the giant landslide in its epicentral zone, we checked the validity of the dependence between the volume of the maximal landslide and the magnitude of the responsible earthquake for Gornyi Altai. According to calculations based on the ArcView software and the contour provided by the GPS survey, the total landslide area is 0.66 km^2; the volume based on the empirical formula [7] is 0.027 km^3; and the length of the detachment wall is 1.1 km. As seen in the figure, the point corresponding to parameters of this landslide and M = 7.5 [8] completely falls into the interval of the standard deviation of the function. We may have to wait for a long time to make the next control point, because the Chuya earthquake in 2003 is thus far the only instance in Gornyi Altai history that gave us a chance to correlate precisely the magnitude of a major seismic event with its consequences in the topography. The data presented above have confirmed the applicability of the estimated dependence between the maximal landslide volume and the earthquake magnitude for the Altai region.

In addition to the volume of the landslide body, the length of the detachment wall represents another informative parameter for the description of landslides. The formation of a landslide body is accompanied by forces of its destruction (degradation of ice in the loose permafrost, erosion, landslides, slumping, and so on) and, hence, a decrease in its characteristic area and volume. Therefore, the values of the paleoseismic magnitude based on the analysis of parameters of the related landslide body represent the lower estimates. In contrast, the length of the detachment wall commonly increases as a result of most exogenous processes. Hence, values of the paleoseismic magnitude based on the analysis of the detachment wall length represent the upper estimates. In the case of similar values of magnitudes of old earthquakes and the Chuya earthquake, one can use an ordinary linear dependence for estimating the relationship between the length of the detachment wall of the maximal old landslide and the magnitude of the responsible earthquake.

We studied the paleoseismicity of Gornyi Altai based on the four largest and best preserved old landslides, which were mapped in the transition zone between the South Chuya Range and the Chuya intermontane depression. This area is confined to the Taldura, Chagan, and Elangash river valleys in the Chuya earthquake region (M = 8–9) [9]. The concentration of specific landforms, large dimensions of accumulative bodies, and their confinement to boundaries of morphostructures allow a reliable identification of their seismic origin. The whole system of landslides under consideration probably formed in the latest Pleistocene–Holocene, since they deform Late Pleistocene moraines. Despite the small number of landslides, they represent a wide age range of earthquakes. The inference on the successive origin of seismic dislocations is based on analysis of the integrity of landslide bodies



Dependence of the maximal landslide volume (logarithmic scale) on the earthquake magnitude. The bold line shows the calculated dependence; dashed lines denote the standard deviation; the box marks the volume of the maximal landslide (0.027 km^3) caused by the Chuya earthquake in 2003 and the earthquake magnitude (7.5).

and their distance from the detachment wall. It should be emphasized that the distance between old landslide masses and the detachment wall in loose permafrost areas reflects not the intensity and direction of a seismic shock but the duration of ice degradation and the downslope sliding of a landslide body that depends to a greater extent on the slope steepness. Landslides 2 and 3 are related to earlier seismic events. Landslide 4, the best preserved and the closest to the detachment wall, is related to the latest paleoseismic event. Landslide 1, characterized by the largest size among the discussed paleoseismic dislocations, is probably related to a very strong earthquake, the magnitude of which could be close to the highest possible value (table). Difficulties associated with the estimation of magnitudes of the strongest old earthquakes are characteristic of other active seismic regions as well [4]. Therefore, estimates of the magnitude of the old earthquake responsible for landslide 1 yield a very wide range of possible values.

The magnitude of the old earthquake responsible for landslide 4 is estimated with an accuracy of 0.5, which coincides with the precision of estimation of magnitudes of old earthquakes based on fractures in the topography of the Pamirs and Tien Shan [3]. For older earthquakes (landslides 2 and 3), the scatter in the lower and upper estimates of magnitudes is 1.3.

Thus, we have estimated for the first time the magnitude of old earthquakes in Gornyi Altai based on the calculated relationship between the earthquake magnitude and landslide parameters (volume of the landslide

Parameters of seismogravitational displacements mapped in the epicentral zone of the Chuya earthquake in 2003 (1–4) and calculated earthquake magnitudes

Landslide	$S_{L_{max}}$, km^2	$V_{L_{max}}$, 10^{-3} km^3	L_{Det}, km	M_{min}	M_{max}
1	0.35	10.44	1.4	7.1	9.5
2	0.23	5.44	1.20	6.9	8.2
3	0.33	9.48	1.22	7.0	8.3
4	0.30	8.22	1.1	7.0	7.5
Recent	0.66	27.0	1.1	7.5	7.5

Note: ($S_{L_{max}}$, $V_{L_{max}}$) area and volume of the maximal landslide caused by one seismic event; (L_{Det}) length of the detachment wall; (M_{min}, and M_{max}) lower and upper estimates of magnitudes of the seismic event.

body and length of the detachment wall related to the maximal seismogravitational displacements). Based on the case history of a landslide in the epicentral zone of the Chuya earthquake with $M = 7.5$, we have checked the applicability of the calculated dependence of the maximal landslide volume on the earthquake magnitude for the Altai region. The use of this relationship allowed us to obtain lower estimates of magnitudes for old earthquakes. The linear dependence between the detachment wall length and the earthquake magnitude yields the upper estimate of magnitudes of old earthquakes that caused gravitational deformations similar in volume to the maximal landslide during the Chuya earthquake. The calculated magnitudes of paleoseismic events provide the estimated precision acceptable for the paleoseismogeological method. The younger the seismic event, the higher the precision. Giant landslides mapped at the southern boundary of the Kurai–Chuya system of intermontane depressions mark the NW-trending seismogenerating dextral fault zones extending from Mongolia [6, 10]. Magnitude estimates of old earthquakes (from 6.9 to the maximum possible) based on these seismic dislocations indicate that the Gornyi Altai region was characterized by a higher seismicity during the whole Holocene than was assumed previously. These estimates confirm the concept of a common seismotectonic environment of the Gornyi and Mongolian Altai regions and make it possible to apply the proposed method for estimating the seismicity of the entire Altai region.

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