A Detailed Study of the Seismic Régime in the Garm Epicentral Region (*)

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The Garm region of the USSR, like California in the USA, is a true earthquake laboratory. Here and there earthquakes not only often occur and reach high intensities, but they are also being systematically studied on the basis of instrumental data. That is why the results obtained in these regions (and in a few other regions of the globe) become to a great extent of general seismological importance.

From 1955 on, according to a sufficiently complete program, continuous observations of the seismic regime were carried out in the Garm region. Seismic régime we understand as the entire complex of earthquakes considered in time and space. Into our program the earthquakes with origins in the earth's crust were included. Their seismic energie E (being related to a sphere of a radius $R = 10$ km surrounding the hypocentre) varying within a range of 10^{12}-10^{17} joules. The investigations were carried out mainly in the 10^{6}-10^{14} joules range.

In studying the energy distribution of the yearly earthquake number N in the Garm region the slope $\gamma = -\Delta \log N / \Delta \log E$ of the earthquake " occurrence graph " $N(E)$ was found to be only slightly varying with time and space (i.e. from one region to another one) notwithstanding the possible essential change in the general seismic activity (Fig. 1). For the Garm region, as seemingly for most seismoactive regions of the globe, this slope is on the average $\gamma = 0.43 + 0.05$ (Fig. 2).

It is of interest to compare these data (as it was done in ([2])) with Gutenberg's statistics for the yearly number of shallow earthquakes (with foci in the earth's crust) occuring throughout the globe. Fig. 3

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represents this statistics. Here N_Σ is the total number of earthquakes exceeding in magnitude m a given value. The magnitude m is expressed

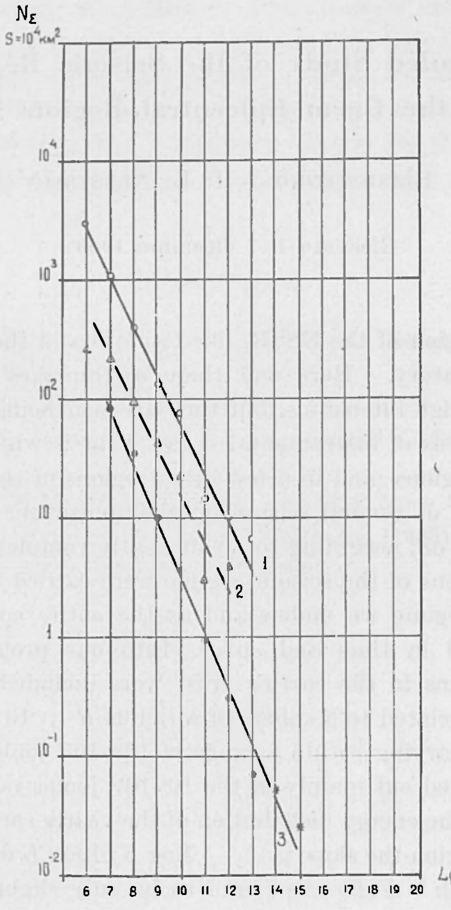

Fig. 1 – Earthquake occurence graphs for separate portions of the Stalinabad-Garm region: 1) Peter the Great ridge, area 1200² km²; 2) the Karakul rupture, area 1500 km²; 3) the Stalinabad region, area 14.400 km².

in the unified Gutenberg's scale. This magnitude is connected with the seismic energy by the following relation (³)

$$\log E_{\text{ergs}} = 5.8 + 2.4\ \text{m} \quad \text{or} \quad \log E_{\text{joules}} = -1.2 + 2.4\ \text{m} \qquad [1]$$

wherefrom follows that

$$\gamma = - \frac{d \log N}{d \log E} = - \frac{1}{2.4} \frac{d \log N}{dm} . \qquad [2]$$

Only the most reliable part of Gutenberg's statistics (3) was used in our calculations (2), namely that of the magnitude interval $4.25 \leqslant m \leqslant 7$.

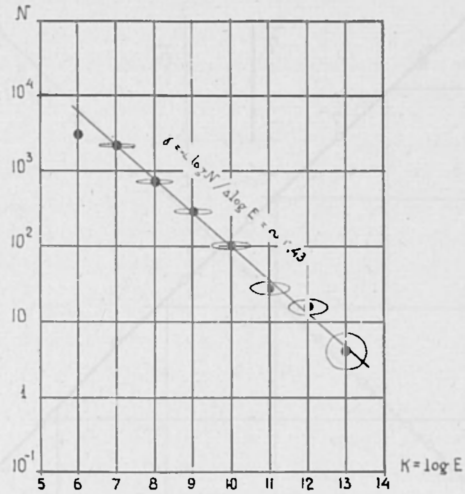

Fig. 2 – Earthquake occurence graphs for the Garm region over the time interval 1955-1957. The size of the ellipses indicates the errors of determinations.

The values of density $N = - dN_\Sigma/dm$ of the earthquake magnitude distribution was determined (see fig. 4) by graphical (open circles) as well as by numerical (crosses) differentiation. Both methods gave practically the same results. The slope $g = - d \log N/dm$ of the averaging graph in this interval was 0.98, which according to [2] corresponds to $\gamma = 0.41$. This value, as one can see, corresponds within the limit of errors to that for the Garm region ($\gamma = 0.43 \pm 0.05$).

It may be noticed that Gutenberg himself using the less reliable part of his statistics (for $m < 4.25$) obtained $g = 0.92$ which corresponds to $\gamma = 0.38$. The discrepance between his values and ours ($g = 0.98$ and $\gamma = 0.41$) is relatively small and in principle of no great significance.

Approximate constancy of the average values of γ in time and space was confirmed by later observations in the Garm region as well as in other regions of the USSR, carried out by the unified "Garm" technics([5-9]) Less refine methods gave sometimes different numerical results, but

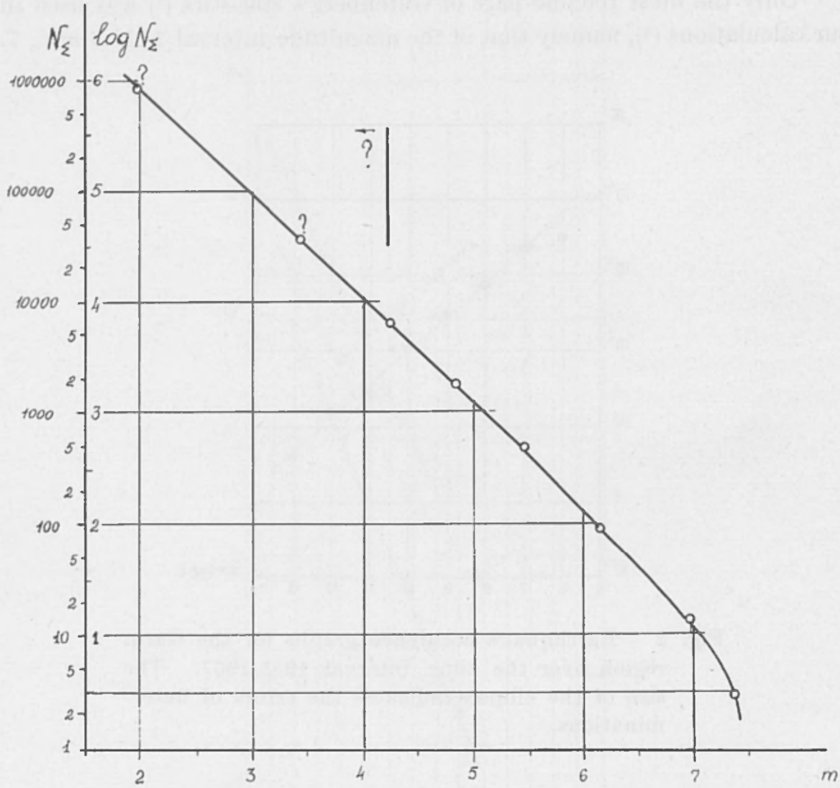

Fig. 3 – The yearly number N_Σ of earthquakes throughout the globe (with foci in the earth's crust) exceeding in magnitude a given value (according to Gutenberg's statistics, 1956).

almost all soviet and foreign scientists agreed at least on the point that practically everywhere an approximately linear dependence of log N *vs* log E was observed in a more or less wide energy range (see ([10-16]) and oth.). It should be pointed out that our observations contradict Tsuboi's new formula ([16]) according to which the slope of the occurence graph depends on the seismic activity in the weak energy range.

In fig. 5 a collection of occurence graphs $N(E)$ is presented for a number of regions of the globe and for the Earth in total (for the shallow earthquakes). What strikes the eye, is the approximate parallelism of all the graphs, so that each of them can be approsimately expressed by the formula

$$\log N = C + \gamma \log E \,, \qquad [3]$$

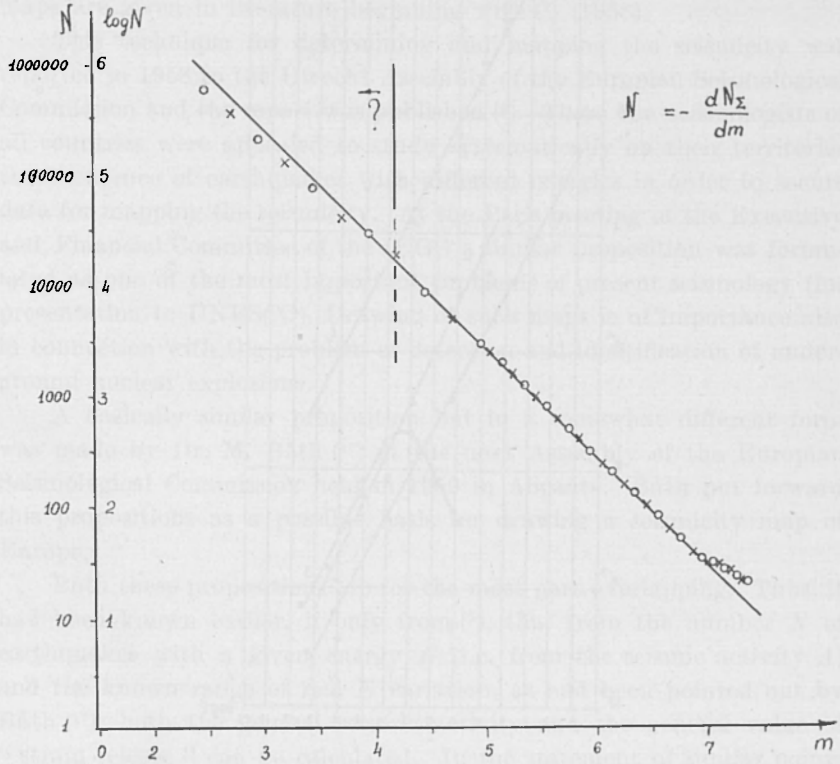

Fig. 4 – The earthquake occurence graph for foci in the earth's crust throughout the globe (according to Gutenberg's statistics, 1956).

where $\gamma =$ const and C is a parameter depending on space coordinates and possibly on time.

Although the idea of approximately constant slopes of the earthquake occurrence graphs in different regions of the globe requires further checking, studying, more accurate definition and probably a certain limiting, it still might be included as one of the main prerequisites to a development of a quantitative method for determining the *average seismicity*, at least as a first approximation.

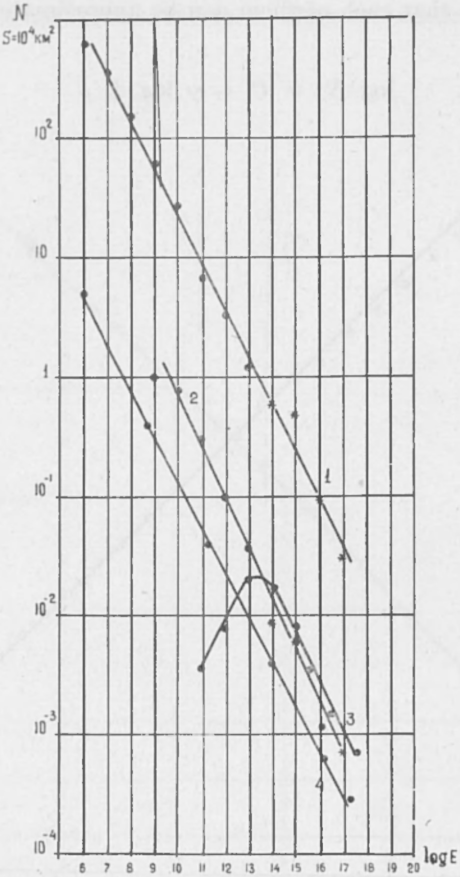

Fig. 5 – Earthquake occurence graphs for a number of seismoactive regions: 1) the Garm region of the USSR; 2) California, USA; 3) Japan and the adjoining regions; 4) the globe.

At the Moscow session of the Seismological Council of the Ac. Sci. USSR held in 1957 a new quantitative method (1) for the determination of the seismic activity from the *level C* of the occurence graph (see equation [3]) was first proposed. This method was based on the idea of approximately constant slopes of the occurence graphs.

Here as a mesure of the seismic activity A may be chosen the yearly number N of earthquakes of some fixed class K of earthquake energy $E = 10^{K+0,5}$, for instance, for $K = 10$, referred to a definite area unit S (or volume unit) of the region under investigation, let us say, for $S =$ 10.000 km². A similar measure of activity may be obtained on the basis of magnitudes instead of energies E. To represent spatial distribution of activity, maps are drawn in isolines of the quantity A. Samples of such maps are given in literature beginning with (1) (1958).

This technique for determining and mapping the seismicity was reported in 1958 to the Utrecht Assembly of the Europian Seismological Commission and the report was published (5). There the seismologists of all countries were appealed to study systematically on their territories the occurence of earthquakes with different energies in order to secure data for mapping the seismicity. At the Paris meeting of the Executive and Financial Committee of the IUGG a similar proposition was formulated as one of the most important problems of present seismology (for presentation to UNESCO). Drawing of such maps is of importance also in connection with the problem of detection and identification of underground nuclear explosions.

A basically similar proposition but in a somewhat different form was made by Dr. M. Bath (17) at the next Assembly of the Europian Seismological Commission held in 1959 in Alicante. Båth put forward this propositions as a possible basis for drawing a seismicity map of Europe.

Both these propositions are for the most part overlapping. Thus, it had been known earlier, if only from (5), that from the number N of earthquakes with a given energy E (i.e. from the seismic activity A) and the known range of real E variation, as had been pointed out by Båth (17), both the general seismic activity and the general value of " strain release " can be calculated. In the statement of similar points both propositions (5) and (17) coincide.

There is however a difference between these propositions in the choice of the departure of reference quantity. It is quite natural to desire this reference quantity to be determined with the greatest possible stability, accuracy and detailing.

We considered and still consider now as the most suitable reference quantity the number N of earthquakes with some fixed, average for a given region, energy E, i.e. the seismic activity A. On no account should the number of earthquakes having a " maximum " energy E_2 for this region or a maximum magnitude M_2 be chosen as the reference quantity.

Neither can the values E_2 or M_2 themselves be used for this purpose. The fact is that earthquakes of a maximum energy rarely occur in the same region. A still rarer event is the occurence of a very strong earthquake in one and the same place. Each new strong earthquake originates in a new region, though sometimes close to the region of the previous earthquake. Stable statistics on strong earthquakes might be obtained only over time intervals of many thousands of years. This excludes keeping account of average numbers of strong earthquakes over limited time intervals from instrumental data from which the most objective information is expected.

However, as might be inferred from ([17]) Bàth proposed to choose as reference quantities just the " maxima " earthquakes with magnitudes M_2, originating during a time unit on this or that territory. Although this proposition implies that the energies of the " maxima " earthquakes are not fixed and that as such any of the strongest earthquakes might be chosen, they still are single events. That is why the average frequency of such earthquakes fluctuates strongly. And accordingly as strongly fluctuates also the average energy generated by these earthquakes, which constitutes a lions share of the general average energy of all earthquakes. The same refers also to the strain release. If we relied upon the maxima earthquakes M_2 as reference quantities, then this would inevitably lead us to a decrease in accuracy and detailing of the spatial distribution of seismic activity when trying to map it. This had been pointed out several times in our publications ([1 4 5]) and also in those of others. From this point of view Bath's proposition in form ([17]) seems unrational.

In ([17]) was alos suggested that it might be sufficient to draw maps only of one of the related quantities: M_2, A, (N for a given E) for a summary energy or for a general value of the strain release, since all other quantities, according to Bath's statement, are obtained single-valued from these. This simple and convenient statement is unfortunately only formally correct under certain conditions, which are in fact not always fulfilled. At present very little is known yet about the behaviour of the $N(E)$ dependence in the region of " maxima " earthquakes for any area. However, regions undoubtedly exist in which the seismicity is limited by moderate seismic energies E and stronger earthquakes are not observed even over very long time intervals. It seems as if in these regions the occurrence graphs $N(E)$ are interrupted at some maxima values of $E_{\max} = E_2$ different for different regions.

If so, then for complete quantitative characteristics of the seismic activity in different regions, they should be described by at least two quantities: by the seismic activity A in the area of moderate earthquakes energy and by the energy E_2 of " maxima " earthquakes. And accordingly the A maps should be supplemented by E_{max} maps.

Moreover, it would be more cautious to draw also maps of γ, since it was only conditionally considered as constant. Perhaps later on will be possible within a definite range to put with a definite accuracy $\gamma =$ const. But this problem requires further study: obsevations under natural conditions of the earthquakes themselves and further theoretical and experimental work (see e.g. ([18-21])).

Up till now the determination of long term average seismicity was considered. Now the important problem of time variation of seismicity will be discussed. This problem was extensively studied by Benioff. His known works deal with it in relation to the entire globe and its local parts and also to limited processes, such as aftershocks of strong earthquakes. To characterize quantitatively the seismicity Benioff used a certain " strain release " value.

We shall give here some data on the time variation of seismicity obtained in the Garm-Stalinabad region, characterizing the seismicity by another value — the seismic activity A for earthquakes with energies of 10^{10} joules (10^{17} ergs). For a comparison a similar example from data on California (Kern County) will be given.

Determination of the time variation of A started at the moment a strong earthquake occured in the given region: Khait (1949, $M = 7{,}75$); Kern County (1952, $M = 7{,}6$); Nurek (1956, $M = 5{,}5$); Chatkal (1946, $M = 7{,}5$). Immediately after a strong earthquake the seismic activity, as known, changes most sharply and these data are therefore the most obvious. The value of A (normalized over an area of 10^3 km^2 and a time interval of one year) corresponding to different time intervals was plotted against time on a double logaritmic coordinate system in fig. 6. Here the ordinates are values of A and the abscisse — time intervals t following the strong earthquake. Notwithstanding the difference in the nature of regions and in the intensity of the initial shock, the way in which the activity changed with time was about the same in all cases under consideration and it could be described by the formula:

$$A = \frac{a}{b + t^n}, \qquad [4]$$

where $b = \text{const} \ll 1$, $n \cong -\Delta \log A/\Delta \log t$ is the slope of these graphs (close to 1); a — a constant characterizing the average activity level over the first year following the principal shock.

n is probably not a universal constant and may change from region to region and from time interval to time interval. However, data which would permit the determination of time variation of n are at present not available.

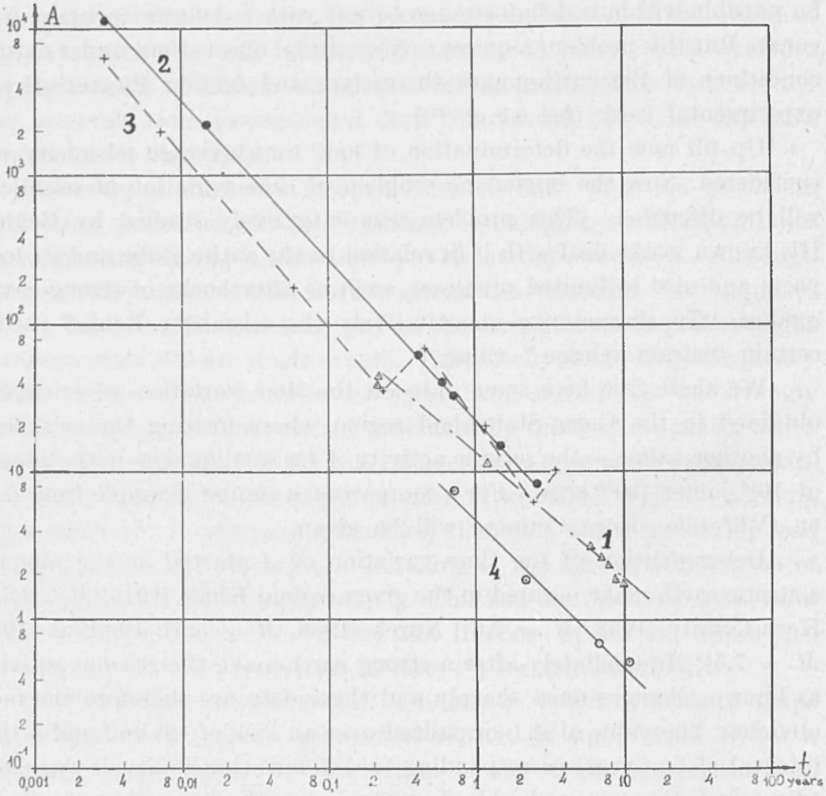

Fig. 6 – Time variation of the seismic activity after a strong earthquake: 1) Khait, 1949, M = 7.7 (n = 0,9); 2) Kern County, 1952, M = 7.6 (n = 1.1); 3) Nurek, 1956, M = 5.5 (n = 1.2); 4) Chatkal, 1946, M = 7.5 (n = 10).

The time dependence of $A(t)$ in form [4] (see also fig. 6) shows that the seismic activity A may vary very strongly with time, so that a long enough time after a strong earthquake the activity level of a local seismoactive region may become very low. This is well known from observations carried out in epicentral regions of past strong earthquakes. But reverse cases are also known: in regions, which had been quiet up to a certain moment, new seismicity originated (or recommenced after a long interruption) and not necessarily with a strong earthquake at the beginning. For that reason formula [4] cannot be considered as a universal one. However, this formula describes relations we are very often confronted with. Similar relations were also observed for processes more limited in time and space: for subsequent shocks of moderate earthquakes and also when carrying out experiments on rock pressure in mines ([20]).

The above given examples show that short-term observations of seismic activity in any region might lead to errors in establishing its *average* activity. Nevertheless the existence of a certain regularity in the time variation of activity after a strong earthquake permits to use it under additional conditions for an estimation of the average value of activity A if the time course of A during a sufficient interval of time is known.

CONCLUSIONS.

As a result of a detailed investigation of the seismic regime in the Garm-Stalinabad epicentral region of the USSR some methods were developed for a quantitative determination of the seismicity. It seems possible now to draw the following conclusions:

1. As the principal value suitable for a quantitative characteristic of seismicity, the average seismic activity A may be used, that is the occurence frequency N of earthquakes with some fixed seismic energy E at the focus.

2. At the same time the maximum energy E_{max} of earthquakes occuring in the given region and the slope of the $N(E)$ " occurence graph" should be also determined.

3. The same quantities — A, E_{max}, γ should be used in mapping the seismicity.

4. When estimating the long-term average values of activity A from short-term observations of this quantity, the time variation of A should be taken into consideration. In a number of cases the form of the time variation $A(t)$ was determined, t being the time elapsed from the last strong earthquake.

5. Regularities concerning the quantities A, γ, E, t and others require further more exact determination, limiting and detailing. For

this purpose accumulation and assimilation on an international scale of the factual material on earthquakes of the entire globe, obtainedmainly by instrumental and quantitative methods, would be necessary.

SUMMARY

As a result of 5 year detailed instrumental study of earthquakes in the Garm-Stalinabad region of the Tadjik SSR (USSR) a method of quantitative determination of seismic activity A has been elaborated. The value A represents the frequency of occurrence of earthquakes on a given area and in a given energy ranges where the number of earthquakes is large enough to derive stable statistic conclusions. It is not a fait way to give a quantitative appraisal of the seismicity referring to the frequency of occurrence of maximal earthquakes which occur rarely and therefore their parametres fluctuate to a large extent.

From another side, a sound appraisal of seismicity must include, besides of A, the data on the strongest earthquakes known in a region under investigation.

A special study on the time changes of the seismic activity A after strong earthquakes leads to a conclusion that in some instances the value of A varies approximately in an inverse proportion to the time interval elapsed since the moment of the strong earthquake.

RIASSUNTO

Quale risultato di 5 anni di studio strumentale particolareggiato sui terremoti nella regione Gram-Stalinabad della Repubblica del Tadjik (URSS) è stato elaborato un metodo di determinazione quantitativa dell'attività sismica A. Il valore A rappresenta la frequenza di produzione dei terremoti in una determinata area e secondo cammini stabiliti, dove il numero dei terremoti è sufficientemente grande da poterne trarre sicure conclusioni statistiche. Non è facile dare un apprezzamento quantitativo della sismicità riferendosi alla frequenza di produzione dei terremoti più grandi che si verificano raramente e i cui parametri perciò variano entro limiti molto vasti.

D'altro canto una giusta valutazione della sismicità deve comprendere, oltre A, i dati sui terremoti più forti noti in una regione sotto controllo.

Uno studio speciale sui mutamenti di tempo dell'attività sismica A dopo forti terremoti, conduce ad una conclusione: che in alcuni casi il valore di A varia approssimativamente in proporzione inversa all'intervallo di tempo trascorso dal momento del forte terremoto.

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