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Acta Universitatis Carolinae. Mathematica et Physica, Vol. 17 (1976), No. 2, 49--74

1976 ACTA UNIVERSITATIS CAROLINAE – MATHEMATICA ET PHYSICA VOL. 17, NO. 2, Pag. 49–74

The Character of Seismic Activity in Europe

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Received 25 May 1975

The earthquake foci are not evently distributed all over Europe but are concentrated in certain areas. On the basis of this reality we divide Europe into partial regions and we investigate the seismic activity of these partial regions. The study of seismic activity of an region requires the investigation of the earthquakes of this region only from the viewpoint of their effects and intensity but particularly from the viewpoint of time and space distribution of shocks on the basis of which we obtain important information on dynamic processes in the Earth's crust and the upper mantle. The present results show that the character of seismic activity in individual partial regions of Europe is rather different; these regions differ from each other by different values of the parameters of the magnitude-frequency relation, the number of earthquakes, the value of the greatest earthquake that can be expected in one or another region, the types of earthquake sequences occurring in individual regions and also by migration of foci in horizontal and vertical planes.

Очаги землетрясений в Европе распространены неровномерно и они сосредоточенны в определённых областях. На основе этой действительности разделяем Европу на частичные области и расследуем сейсмическую активность этих частичных областей. Изучать сейсмическую активность определенной области значит исследовать землетрясения этой области не только из точки зрения их действия и величины, но и из точки зрения распределения толчков во времени и в пространстве, на основе которого мы получаем важные информации об процессах в земной коре и во верхной мантии. Предъявленные результаты показывают что частичные области Европы отличаются по характеру сейсмической активности; они отличаются разными величинами параметров зависимости между числом землетрясений и магнитудой, числом землетрясений, величиной самого большого толчка который можно ожидать в определённой области, типами серий землетрясений которые появляются в отдельных областях и тоже миграцией очагов в горизонтальной и вертикальной плоскости.

Ohniska zemětřesení nejsou rovnoměrně rozprostřena po celé Evropě, nýbrž jsou koncentrována v určitých místech. Na základě této skutečnosti dělíme Evropu na dílčí oblasti a vyšetřujeme zemětřesnou činnost těchto dílčích oblastí. Studovat zemětřesnou činnost určité oblasti znamená zkoumat zemětřesení této oblasti nejen z hlediska jejich účinků a mohutnosti, ale zejména z hlediska časového a prostorového rozložení otřesů, na základě čehož získáváme důležité informace o dynamických procesech v zemské kůře a ve svrchním plášti. Předložené výsledky ukazují, že jednotlivé dílčí oblasti Evropy se liší charakterem zemětřesné činnosti, tj. liší se od sebe různými hodnotami parametrů magnitudo četnostního vztahu, počtem zemětřesení, hodnotou největšího zemětřesení, které je možno očekávat v té či oné oblasti, typy zemětřesných posloupností, které se v jednotlivých oblastech vyskytují a také migrací ohnisek v horizontální a vertikální rovině.

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1. Introduction

The study of seismic activity of an region as a whole requires the investigation into the earthquakes of this region not only from the viewpoint of their effects and intensity but particularly from the viewpoint of time and spatial distribution of shocks. The time and spatial distribution of seismic activity provides important information on dynamic processes in the Earth's crust and the upper mantle. In order to obtain an overall picture of the processes in the Earth it is necessary to investigate also the mutual connection of seismic activity with the volcanic and tectonic activities and the relation to the geological structure of the area. In the following paragraphs results will be summarized that were obtained from the study of the character of seismic activity in Europe, and the probable connections of seismic and volcanic activities will be pointed out. Considerations and results will refer to Europe according to the definition used by the European Seismological Commission i.e. Europe and the coutries along the Mediterranean Sea.

The seismic activity of a certain area is objectively determined by the amount of energy released during the shocks. The main part of this energy is released during strong earthquakes although weak earthquakes prevail as to the number. From [1] it follows that from the annual number of more than 100 000 earthquakes registered on the average, there is generally only one earthquake whose magnitude is greater than 8, about 10 earthquakes are of the magnitude 7—8, about 100 of the magnitude 6—7 a.s.o. From the relation between the earthquake energy and the magnitude it can be ascertained that only one earthquake of the magnitude 8 possesses almost as much energy as the rest of earthquakes altogether. In view of this fact, the activity in the region of the Pacific Ocean comes to the foreground and the significance of seismic activity in Europe declines. Roughly speaking, approximately 3—4% of the energy released in the world during earthquakes is released in Europe. The most active area of Europe is Greece where about half this energy is released.

2. Characteristics of Seismic Activity

The main parameters of each shock are the latitude φ, the longitude λ, the depth of focus h, the hypocentral time H (the time of the earthquake origin), and the quantity, which objectively characterized the size of the earthquake. The size of the earthquake will further be characterized by the quantity magnitude, which is an objective measure of the seismic energy of the earthquake i.e. of that part of energy released in the focus of the earthquake that is carried by seismic waves. This quantity was introduced by Richter in 1935. The original definition was later extended and adapted. In accordance with the agreement of International Association of Seismology and Physics of the Earth's Interior (IASPEI) in Zürich in the year 1967, the magnitude is determined according to the relation

$$M = \log (A/T)_{\max} + \sigma(\Delta) \qquad \text{for } h \leq 60 \text{ km}$$

and

$$M = \log (A/T)_{\max} + \sigma(\Delta, h) \qquad \text{for } h > 60 \text{ km},$$

where $(A/T)_{\max}$ is the highest relation of the amplitude and the respective period of the investigated phase of the seismic wave; $\sigma(\Delta)$ or $\sigma(\Delta, h)$ are the calibration functions, which compensate for the change of A/T with the distance or with the distance and the depth h. The calibration function depends on the type and the component of the wave, from which the magnitude is determined [2]. According to the focus depth, earthquakes are divided into three groups: shallow earthquakes $h \leq 60$ km; intermediate earthquakes $60 < h < 300$ km; deep earthquakes $300 < h < 750$ km.

To investigate the seismic activity is to study the function $f(\varphi, h, \lambda, H, M)$ in fivedimensional space. This function is mutually unambiguous, that means, each earthquake is given one point in fivedimensional space and vice versa. It is nought in non-seismic areas, for $h > 750$ km and for $E > E_{\max}$ ($E_{\max}$ is the energy of the greatest possible earthquake). The function of five variables is complex and therefore

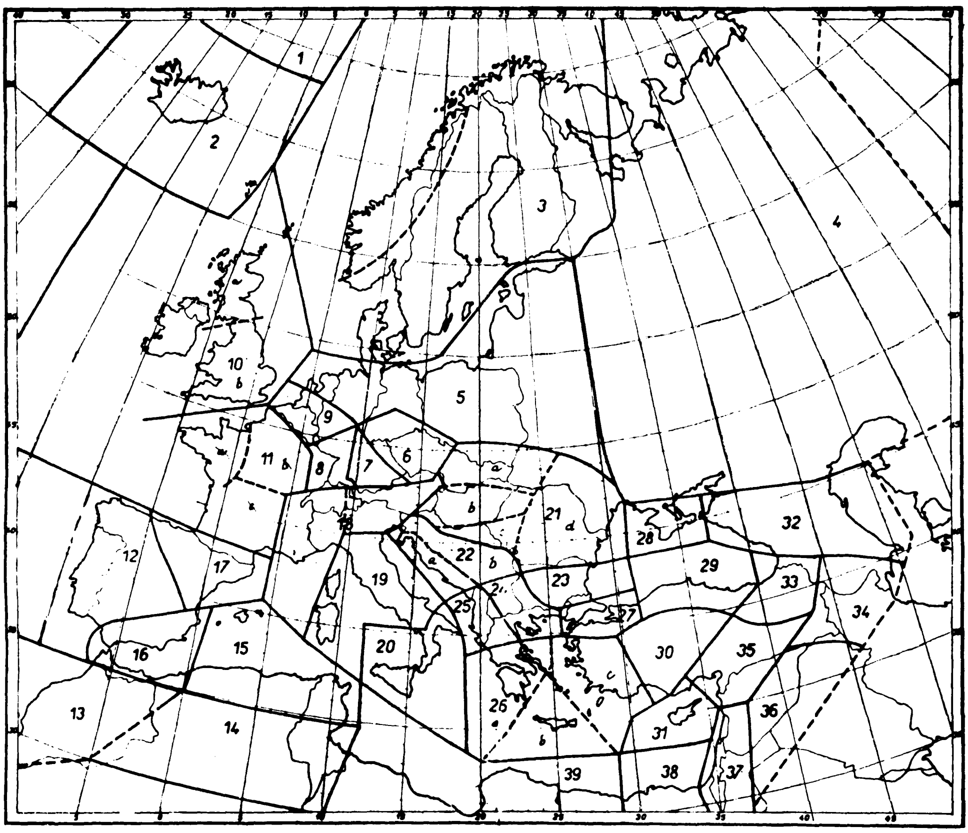

Fig. 1. Partial regions of Europe

it is of greater advantage to investigate partial dependences only. The character of seismic activity of particular regions is described by spatial distribution of epicentres, by the relation between the number of earthquakes and the magnitude, by Benioff's graphs, by the greatest possible earthquake in the given region and by the types of shock groups occurring in that region. Further these relations will be mentioned in greater detail.

Table 1

Author	Relation	Explanation
Gutenberg, Richter	$\log N = a - bM$	N is the number of earthquake with magnitude in interval $(M - dM, M + dM)$, a, b are parameters.
Tsuboi	$\log N = \left(1 - \frac{M}{M_x}\right) \log n_0$	N is the number of earthquakes with magnitude in interval $(M, M + dM)$ in t years, n_0 is a time dependent parameter representing the number of earthquakes with $M = 0$. M_x is the magnitude of the greatest possible earthquake in the given region.
Riznichenko	$\log N = \alpha - \gamma \log E$	N is the number of earthquakes with energy in interval $(E, E + dE)$, E is the energy that passed through the reference sphere*). α, γ are numerical constants. The term energetic class $K = \log E$ (E expressed in joules) is being introduced and the relation is written in the form:
	$\log N = A - \gamma (K - K_0)$	N is the number of earthquakes with energetic class $K \pm 0.5$, $A = \log N_0$, where N_0 is the number of earthquakes with energetic class K_0. It is mostly used $K_0 = 10$. Riznichenko assumes $\gamma =$ constant; $\gamma = 0.4343$.
Ishimoto, Iida	$n(a)\, da = ka^{-m}\, da$	n is the number of earthquakes with the greatest recorded amplitude in the interval $(a, a + da)$, k, m being the numerical constants. By logarithmic calculation of this formula we obtain the linear relation between the logarithm of the number of earthquakes and the logarithm of the greatest registered amplitude. This relation is valid only under quite specific conditions [3].
Neunhöfer	$n(E_i) = \frac{1}{\varphi} \frac{N}{\sigma E_i \sqrt{2\pi}} \exp\left(\frac{-\ln^2 E_i/E_0}{2\sigma^2}\right)$	$n(E_i)$ is the number of earthquakes with the energy E_i; σ, N, E_0 are the parameters; $\varphi = \ln (\Delta E_i)$, where ΔE_i is the size of the class of energy and t is the time of observation.
Purcaru, Zorilescu	$\log N = a + b \log M - c (\log M)^2$	a, b, c are the parameters.

*) The reference sphere is a sphere with the centre in hypocentre and of the radius $R = 10$ km.

2.1. *Spatial Distribution of Epicentres in Europe*

The earthquake epicentres are not evenly distributed all over Europe but are concentrated in certain areas. On these grounds Kárník [2] divided Europe into partial regions, Fig. 1. In the next paragraphs this division will be used in the investigation of seismic activity.

Earthquakes occur mainly along the Mediterranean Sea, mostly on the Balkan Peninsula, especially in its southern part. The most intensive shocks were observed in the area of the North — Anatolian Fault. In Europe only shallow earthquakes occur with the exception of the areas of Vrancea, Crete and Calabria where there are also intermediate earthquakes and in Calabria deep earthquakes as well.

2.2. *Distribution of the Number of Earthquakes to the Magnitude*

The function decribing the distribution of the number of earthquakes according to the magnitude is of great importance in earthquake statistics. A survey of the most frequently used functions is contained in Tab. 1. The relations given in this table are under certain conditions equivalent. Provided the relation between the seismic energy of the earthquake E and the magnitude M can be written in the form $\log E = p + q\,M$, where p, q are the parameters, it was derived in [3] $\gamma = b/q$, $\gamma = (m - 1)/2$ and $b = m - 1$ for the magnitude defined by the relation $M = \log a_{100} + \text{const}$, where a_{100} is the maximum amplitude registered in the epicentre distance 100 km. As determining of the magnitude of the earthquake is easy it is convenient to use the function of the distribution of the number of shocks according to the magnitude.

The dependence between the number of earthquakes and the magnitude must be investigated in the interval ($M_{\min}$, $M_{\max}$) where $M_{\min}$ is the magnitude of the smallest possible and $M_{\max}$ of the greatest possible earthquake in the given area. In determining $M_{\min}$ we are greatly dependent on the network of stations, the sensitivity of instruments and the noise level. In determining $M_{\max}$ we are limited by the short time of observation. The relation between $\log N$ and the magnitude M is usually appro-

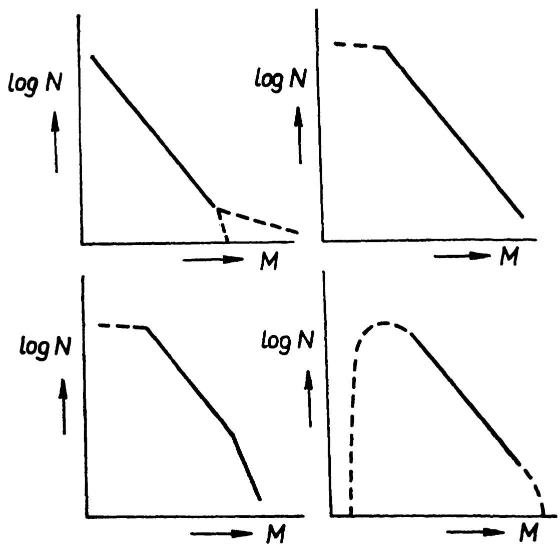

Fig. 2. Different types of dependence log $N(M)$

Table 2

Region	N	The least squares method		The maximum likelihood method		Remarks
		a	b	a	b	
1	99	5.08 ± 0.24	0.70 ± 0.04	4.87	0.66	*
2	149	4.84 ± 0.40	0.63 ± 0.07	4.62	0.62	
3	69	6.41 ± 1.41	1.02 ± 0.25	7.11	1.14	*
12	127	4.15 ± 0.82	0.55 ± 0.13	5.73	0.82	*
15	135	5.80 ± 1.24	0.89 ± 0.23	4.89	0.69	
16	175	6.56 ± 0.43	1.02 ± 0.08	6.15	0.93	
17	59	4.68 ± 0.64	0.72 ± 0.12	4.91	0.77	
18	202	5.94 ± 0.47	0.88 ± 0.09	5.95	0.88	
19	434	6.69 ± 0.19	0.97 ± 0.03	6.56	0.94	
20	184	4.99 ± 0.70	0.70 ± 0.12	5.52	0.81	
21	86	5.21 ± 0.12	0.80 ± 0.02	5.41	0.84	
22	531	7.57 ± 0.52	1.13 ± 0.13	6.92	1.00	
23	76	3.92 ± 0.84	0.55 ± 0.15	4.19	0.60	
24	240	4.54 ± 0.31	0.56 ± 0.05	4.82	0.60	
25	283	6.45 ± 0.88	0.85 ± 0.07	5.45	0.71	*
26	1259	7.35 ± 0.42	0.93 ± 0.10	6.46	0.78	*
27	97	4.22 ± 0.45	0.54 ± 0.07	4.01	0.50	*
29	91	3.90 ± 0.60	0.50 ± 0.10	3.98	0.51	*
30	61	5.43 ± 1.54	0.80 ± 0.27	4.00	0.53	*
32	171	7.67 ± 0.85	1.16 ± 0.15	6.34	0.91	*
33	159	4.71 ± 0.27	0.60 ± 0.04	4.75	0.60	*
34	108	5.16 ± 0.52	0.72 ± 0.10	4.82	0.66	*

ximated by a straight line, exceptionally by two or three, Fig. 2. In this figure it can be seen that function $\log N(M)$ can be approximated by a straight line in a certain interval $(M_1, M_2) \subset (M_{\min}, M_{\max})$; i.e. in this interval it holds

$$\log N = a - bM, \tag{1}$$

where N is the number of earthquakes with the magnitude in the interval $(M, M + \mathrm{d}M)$, a, b being parameters. Besides the simple frequency N, the cumulative frequency of earthquakes can be used to characterize the regions. Under the expression cumulative frequency of earthquakes $N_c(M)$ is understood in seismology the number of earthquakes of a magnitude greater than or equal to M. The cumulative curve begins with great M and in coordinates $(M, \log N_c)$ it aproaches a straight line ant therefore is generally substituted by a straight line. It holds

$$\log N_c = e - fM, \tag{2}$$

where N_c is the cumulative frequency and e, f are the parameters.

The relation between the simple and cumulative frequency is expressed by the relation

$$N_c(M_k) = \sum_{i=k}^{s} N(M_i),$$

where $k = 1, 2, \ldots, s$, s being the number of different magnitude values that were arranged into an increasing series $M_1, M_2, \ldots, M_s$. Naturally the question arises what is the difference between the parameters a, b from equation (1) and the parameters e, f from equation (2). The works [7, 8, 9] start from the assumption of the integral definition of cumulative frequency and derive the relation $f = b$. This, however, has not been confirmed by practical examples [4, 5, 10] and the integral definition cannot be theoretically justified [5, 10].

Numerical values of parameters a, b or e, f characterize the level of seismic activity in the particular region. Parameter a is often called seismic activity. To determine the level of seismic activity, the so called seismic coefficient is sometimes used, which is defined by the equality $c = (1 - b)/a$ [6]. Tab. 2 lists the results obtained for individual European regions using the data from the years 1901–55. In this table in the cases denoted by an asterisk no account was taken in computing the parameters of the first class i.e. $M = 4.1 \div 4.6$ because of the incompleteness of the data in this class. The parameter values are determined by the least squares method and by the maximum likelihood method [4]. The values obtained differ considerably and vary within wide ranges.

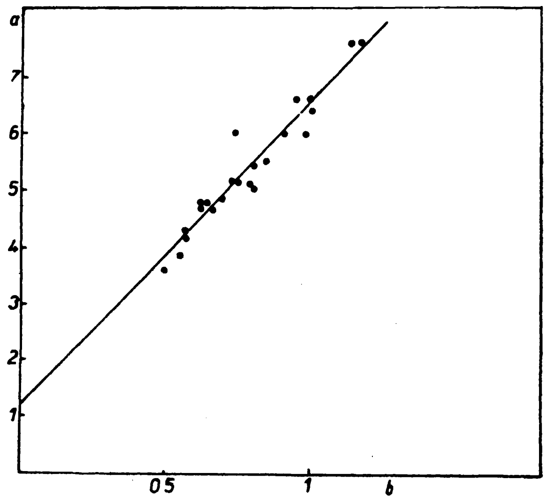

Fig. 3. Dependence $a(b)$; $a = 5.38\,b + 1.20$

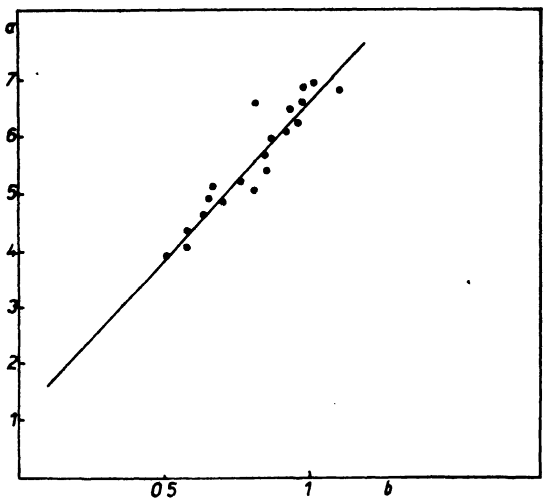

Fig. 4. Dependence $a(b)$; $a = 5.50\,b + 1.10$

Mogi's results [11–13] indicate that the value of parameter b depends on the geotectonic structure of the area increasing with the increasing heterogeneity of the area. The parameter value gives the level of seismic activity in a particular area (from relation (1) it follows that a equals the logarithm of the number of shocks with the magnitude $M = 0$). The higher this value, the higher the

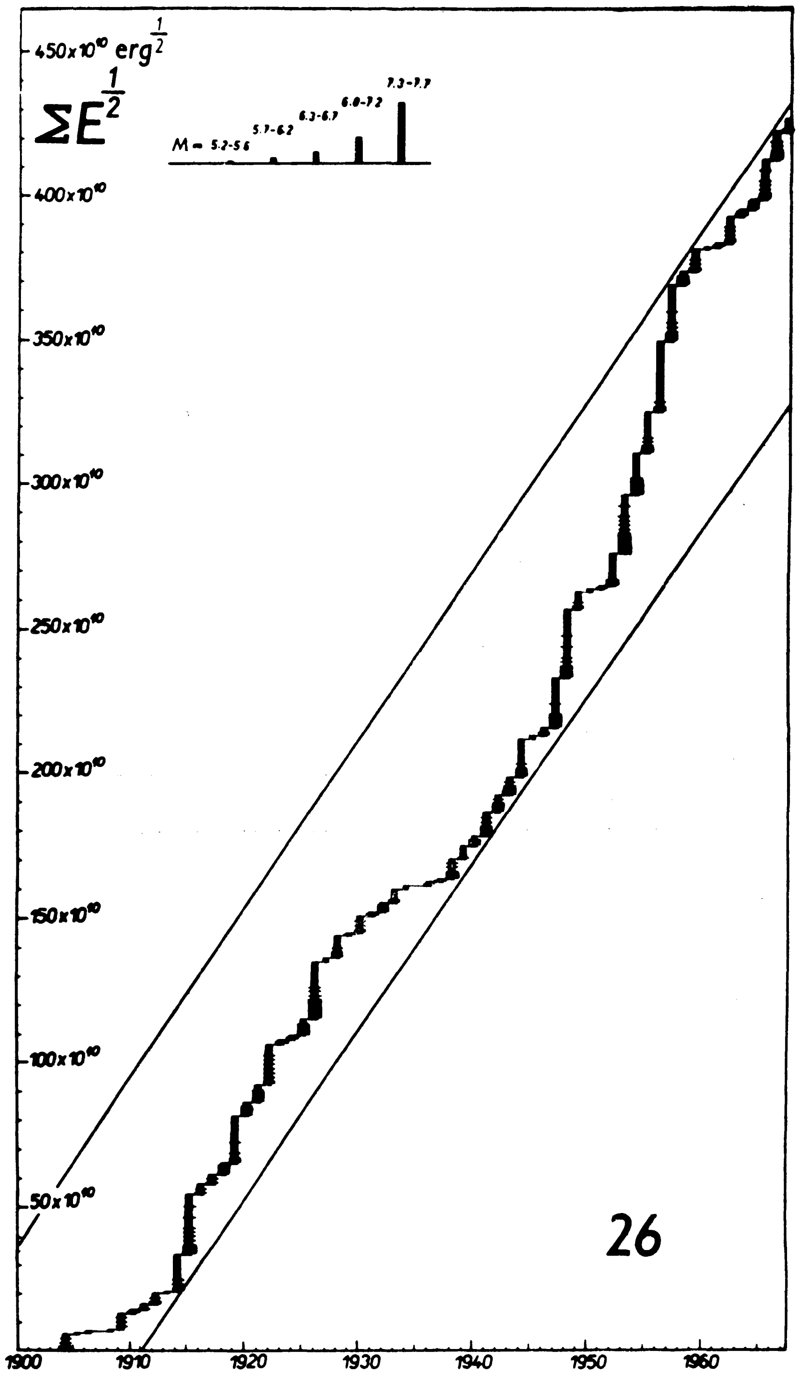

Fig. 5. Benioff's graph for the region 26

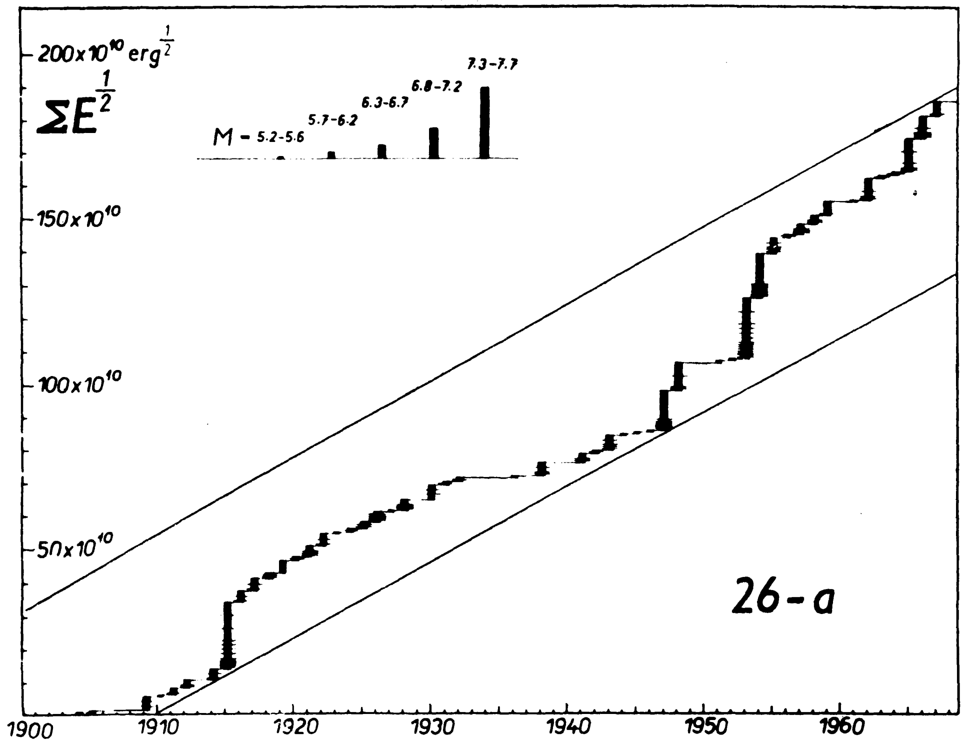

Fig. 6. Benioff's graph for region 26a (Greece)

activity. From Tab. 2 it is evident that in the areas of Balkan where the seismic activity of Europe is concentrated there are high values of this parameter.

From Tab. 2 it follows that parameter a is a linear function of parameter b. This dependence is shown in Figs. 3 and 4. In view of the linear dependence of parameter a on parameter b it can be stated that the seismic regime in a particular region is characterize by one parameter only since the other can be determined from the first according to the present equations.

2.3. *Benioff's Graphs*

Seismic activity can also be considered using the time function $E = f(t)$, called Benioff's graphs.

$$\sum_i E_i^{0.5} = f(t) ,$$

where E_i is the energy released during individual earthquakes and t is the time, Figs. 5–8. In these graphs the vertical lines denote the release of energy. The longer the vertical line is, the more energy is released. The horizontal lines denote the period of "energy cumulation". The period during which energy is cumulated are

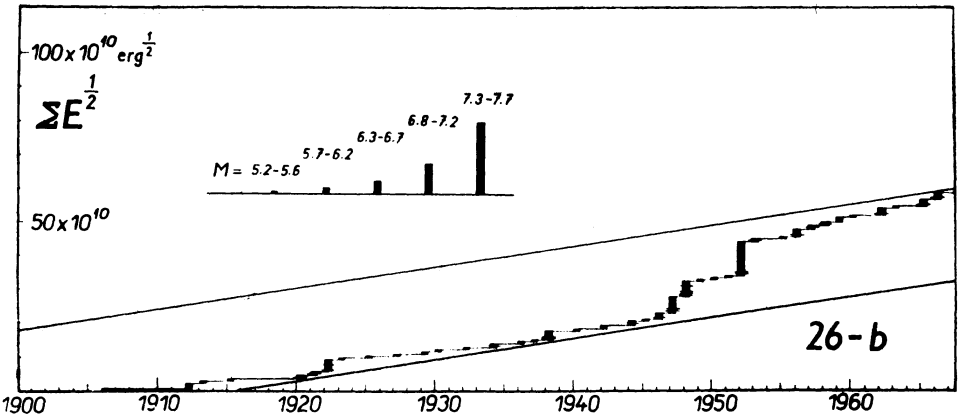

Fig. 7. Benioff's graph for region 26b (the region of Crete)

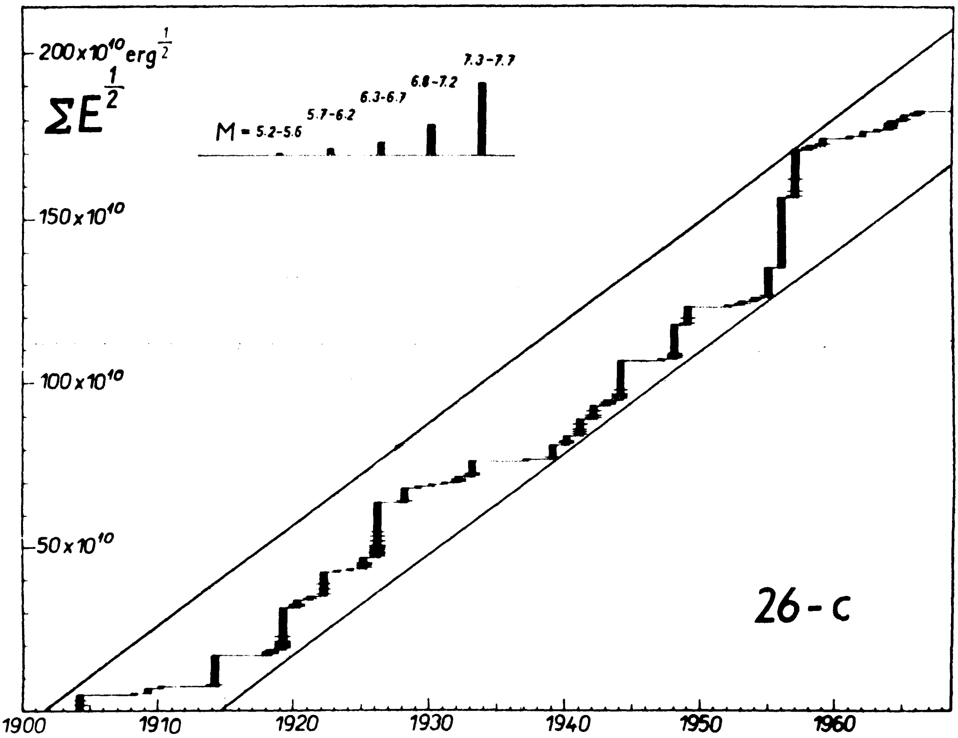

Fig. 8. Benioff's graph for the region 26c (Western Turkey)

called calm and the periods during which energy is released are called active periods. Studying these graphs for the worldwide earthquakes, Benioff came to the conclusion that calm periods are diminishing and that the graphs can be closed into two concurrent lines. The graphs that were constructed later for particular areas do not display this phenomenon.

Benioff's curves depict the process of the release of seismic energy with time. They represent the course of mechanical deformations in the focus sphere with time only in that case if between the total deformation ε_Σ and the released energy ΣE_i holds the relation

$$\varepsilon_\Sigma = k \sum_i E_i^{0.5},$$

where k is the constant. From the theory [21, 22] it follows that $k = \sqrt{2/(p\mu V_i)}$ where μ is the torsion modulus, p is the coefficient of the transformation (conversion) of elastic energy into seismic waves energy and V_i is the focus volume. Direct proportion between seismic energy E and focus volume V is assumed. Owing to this fact a simple relation between the total deformation and the sum of energy roots is incorrect. If we take into account empirically found dependences $\log V = 9.58 + 1.5\,M$ and $\log E = 11.8 + 1.5\,M$, in which V is the focus volume, E the seismic energy of earthquake and M the earthquake magnitude, we obtain by substituting into the equation $\varepsilon_i = \sqrt{2/(p\mu V_i)}\; E_i^{0.5}$ the total deformation in the form

$$\varepsilon_\Sigma = \sum_i \varepsilon_i = k_1 \sum_i E_i^{0.01},$$

where k_1 is the constant. The exponent with energy is 0.01 whereas with Benioff's graphs it is 0.5.

Nevertheless, Benioff's curves provide important information whether the release of energy in a certain period occurred during an intensive earthquake or during a great number of weaker earthquakes. The periods, in which intensive or weak seismic activity took place can be distinguished. Figs. 5–8 give Benioff's curves for the most active region of Europe i.e. for Greece and Western Turkey. Fig. 5 shows the graph for the whole region considered for the period 1901–70. Fig. 6 gives the dependence for Greece; we can see that the active periods took place in the years 1914–32 and 1950–60. A graph for the area of Crete is plotted in Fig. 7 the most active period was in the years 1945–55. A graph for Western Turkey can be seen in Fig. 8, where the active periods occurred in the years 1918–33 and 1939–59. Benioff's curves for other parts of Europe are given in [2]. These figures indicate that strong earthquakes exert a decisive influence on the course of graphs and that weak earthquakes with the magnitude 5 and smaller hardly manifest themselves at all.

Lately, the dependence of cumulative seismic moment M_0 on time has been used to characterize the time regime of regions. The seismic moment is a moment of force couple if the model of focus are two perpendicular dipoles [14, 16]. Aki [17] derived the relation $M_0 = \mu A u$, μ is the torsion modulus, A the area of the fault and u the relative shift of blocks along the fault. An example of this dependence is given in Fig. 9 (taken from [15]). The cumulative seismic moment represents the overall slip of the fault region i.e. the shift of blocks along the fault [14, 15]. The periods with weak seismic activity are characterized by a slight average annual slip and vice versa.

2.4. *The Strongest Possible Earthquake*

To determine the strongest possible earthquake that may occur in a given region is of special importance for judging the degree of danger in that area. Several methods are used to determine the value M_{max}. The best known is Gumbel theory of great values [19] and the method employing parameters of the frequency relation (1): the simple relation $M_{max} = a/b$ [18, 20] holds provided the linear dependence $\log N(M)$ in the interval (M_1, M_{max}). The substance of Gumbel theory of great values is the property of distribution functions of random variable X in the form $F(X) = 1 - \exp(-\beta X)$ that for the division of maximum values Y of this random variable X holds the distribution function in the form $G(Y) = (-\alpha \exp(-\beta Y)) = \exp(-\exp(-\beta(Y - q)))$, where α, β, q are constants that can be determined experimentally from the observed material. The relation $\alpha = \exp(\beta q)$ is valid between these constants. The condition is to define the random variable in an infinite interval so that it can acquire infinite values. Numerical values computed by these methods using the data of the years 1901–55 are contained in Tab. 3, values computed by Gumbel theory of great values were taken from [19]. For the sake of comparison the greatest observed magnitude in this period is also introduced.

From Tab. 3. it is evident that the magnitude computed by means of Gumbel theory of great values is usually one up to two tenths of magnitude unit greater than that actually observed. This comparison suggests that Gumbel theory of great values yields values of M_{max} that are little different from those really observed therefore it seems to be more suitable than the estimate from parameters a, b.

Table 3

Region	The greatest possible earthquake		The greatest observed earthquake
	Gumbel theory	a/b	
1	6.9	7.4	6.5
2	7.4	7.5	7.3
15	6.7	7.1	6.6
16	6.4	6.6	6.3
18	6.4	6.8	6.2
19	6.9	7.0	6.8
21	6.5	6.5	6.4
22	6.7	6.9	6.3
24	7.8	8.0	7.8
25	7.0	7.7	6.7
26a	7.2		7.0
26b	6.5	8.3 (26a–26c)	6.4
26c	7.6		7.4
32	6.2	7.0	6.2
27+29+33+34	8.2	8.0	8.0

From Tab. 3 it follows that the strongest earthquake $M = 8.2$ can be expected in the region of the North-Anatolian Fault which is the sum of partial regions 27+29+33+34. In Greece where most shocks occur and where is the highest seismic activity in Europe, the strongest earthquake of the magnitude 7.2 can be

Table 4

Region	T (years)
1	37
2	77
15	80
16	62
18	56
19	71
21	74
22	29
24	105
25	42
26a	38
26b	71
26c	29
32	125
27+29+33+34	67

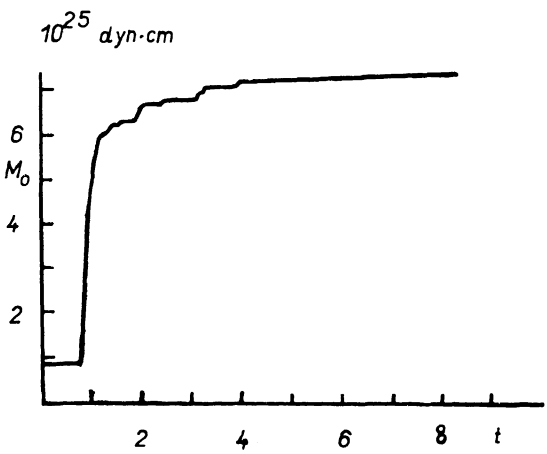

Fig. 9. Dependence of cumulative seismic moment on time; t (days)

expected. From Tab. 3 it also follows that the earthquake of the magnitude $7^3/_4$ can be expected on the territory of Albania and South-East Yugoslavia, i.e. in the regions 24 and 25.

For each region it is necessary to determine on the one hand the strongest earthquake that can be expected in the given area and on the other hand the mean return period of these strong earthquakes. To this aim Gumbel theory of great values can also be used and according to which the mean length of interval T (T is the time between occurrence of two shock with energy Y or greater) is $T(Y) = 1/(1 - G(Y)$, where $G(Y)$ is the distribution function of maximum values of random quantity X. Tab. 4 summarized actual results computed by the above mentioned method [19] for the strongest observed earthquake in the interval 1901–55. From this table it follows that the mean return period of the strongest earthquakes observed is smaller than 55 years, from which relatively reliable data are at our disposal for the regions No 1, 22, 25, 26a, 26c.

2.5. *Types of Earthquake Sequences and Their Spatial Distribution*

The characteristic feature of individual regions are the types of earthquake sequences that occur there. Earthquakes are not an isolated phenomenon. They tend

Table 5. The properties of aftershocks

The number of aftershocks depends on the magnitude of the main shock, on its depth and on the region. It increases with the magnitude of the main shock and decreases with the focus depth. For the Balkan region the relations hold $\log N_0 = 0.95\, M_0 - 0.025\, h - 4.22$ for $h = 14 \div 40$ km; $\log N_0 = 0.95\, M_0 - 0.035\, h - 3.75$ for $h = 41 \div 70$ km, where N_0 is the number of aftershocks of the magnitude $M \geq 4$ [23].
The number of aftershocks in the interval $\mathrm{d}t$ decreases with the time measured from the main shock. The decrease is expressed by the function $n(t) = n_1 t^{-h}\, \mathrm{d}t$, where n is the number of aftershocks in time interval $(t, t + \mathrm{d}t)$, t is the time measured from the main shock and n_1, h are the numerical constants.
The duration time of the aftershock sequency depends direct proportionally on the magnitude of the main shock, indirect proportionally on the epicentre depth and is strongly dependent on the region. In some regions it is several days, in others several months and in some regions it lasts even several years after strong earthquakes.
The total energy released during aftershocks is smaller than 10% of the energy of the main shock. The energy of the strongest aftershock, expressed in ergs, is two to three orders smaller than that of the main shock. The energy of the strongest aftershock is greater than the total energy of all other aftershocks altogether. The energy of aftershocks decreases with the time measured from the main shock. The difference between the magnitude of the main shock and the magnitude of the strongest aftershock increases with the increasing magnitude of the main shock and depends on the focus depth and the region. For Europe it was derived $\Delta M = 0.2 + 0.2\, M_0$ for shallow earthquakes, $\Delta m = -0.8 + 0.4\, m_0$ for intermediate earthquakes [24, 25]. M_0 or m_0 is the magnitude of the main shock, $\Delta M = M_0 - M_1$, $\Delta m = m_0 - m_1$ where M_1 or m_1 is the magnitude of the strongest aftershock. The relations valid in the partial regions of Europe are computed in [24].
The time interval between the main shock and the strongest aftershock decreases with the increasing magnitude of the main shock and depends on the focus depth and the region. For shallow earthquakes in Europe the relation was derived $\log \Delta t = 0.71 - 0.02\, M_0$, where Δt is the time interval between the main shock and the strongest aftershock [24, 25]. The relations valid in partial regions of Europe are computed in [24]. With shallow earthquakes the interval between the main shock and the strongest aftershock is smaller than with intermediate ones. It was found that in 40% cases $\Delta t < 0.5$ day and that in 80% cases $\Delta t < 5$ days [24, 25].

Table 5 (continued)

The distribution of the number of aftershocks according to magnitude is given by Gutenberg-Richter relation $\log N = a - bM$ where a, b are numerical parameters.
The aftershocks of weaker earthquakes have the same epicentre as the main shock. During stronger earthquakes the aftershocks afflict the whole region that is called aftershock region. This is generally of a prolongated elliptic shape and its size depends direct proportionally on the magnitude of the main shock and on the region. The dependence of the size of the aftershock region on the magnitude of the main shock is expressed by the equation derived by Papazachos, i.e. $\log A = 1.46\,M_0 + 5.7$, $A[\mathrm{cm}^2]$, where A is the area afflicted by aftershocks and M_0 is the magnitude of the main shock. As a rule an aftershock region does not originate all at once, its boundaries spread in the direction corresponding to the direction of the fault [21, 26]. The epicentre of the main shock usually lies on the end of the aftershock region and the epicentre of the strongest aftershock on the other end of the aftershock region [23].

to cluster in time and space. There originate groups of schocks, which differ from each other by a different structure and different properties. These groups of shocks are called earthquake sequences. There are several types of them. The types occurring in Europe are given in Fig. 10. Individual types will now be characterized in greater detail.

The group "main shock and aftershocks" is such a group in which the first shock, the co called main shock, is much stronger than the following shocks called aftershocks. The properties of aftershocks in Europe are summarized in Tab. 5.

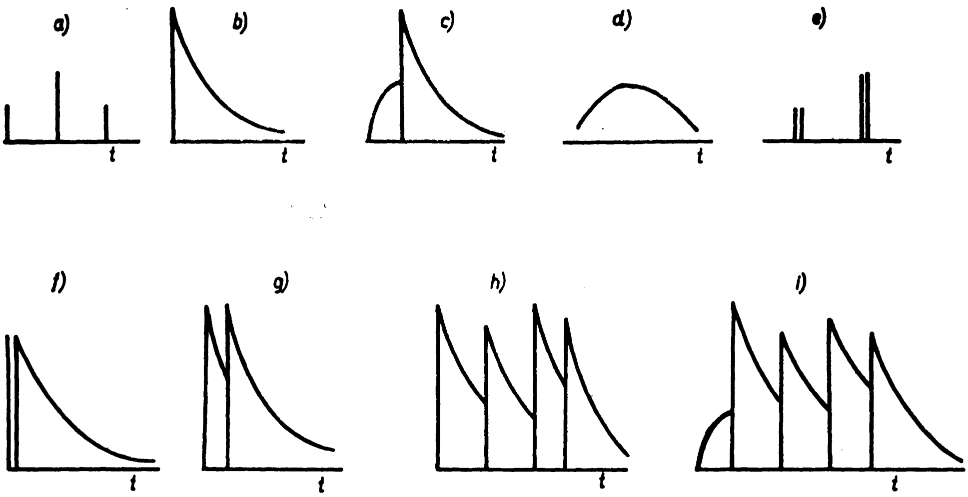

Fig. 10. Earthquake sequences in Europe; time is marked on the horizontal axis and on the vertical axis is the energy released in the time interval $(t, t + dt)$; a) – single shocks, b) – main shock and aftershocks, c) – foreshocks, main shock and aftershocks, d) – earthquake swarm, e) – double shock, f) – i)-multiple earthquake sequences

In the group "foreshocks, main shock and aftershocks", the strongest shock is preceded and followed by weak shocks. The shocks preceding the main shock are called foreshocks. The properties derived for foreshocks in Europe are listed in Tab. 6.

The earthquake sequence of the type "multiple earthquake sequence" is composed of more strong approximately equal shocks, and of weak shocks, which follow each of these strong shocks and have the properties of aftershocks. Two such cases are presented in Figs. 11 and 12. A detailed picture of the properties of multiple earthquake sequences is contained in Tab. 7. This newly defined type of earthquake sequence occurs not only in Europe but also in Japan as confirmed by the investigation of Utsu [27].

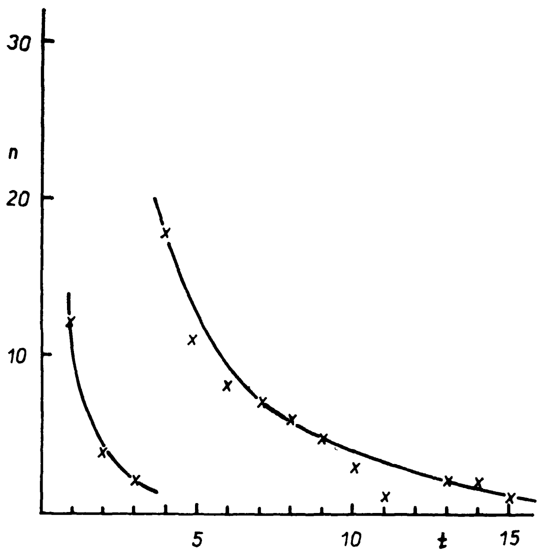

Fig. 11. Multiple earthquake sequence in Yugoslavia in the year 1962; the main shocks were of the magnitudes 5.9 and 6.0, the time interval between the main shocks was 4 days

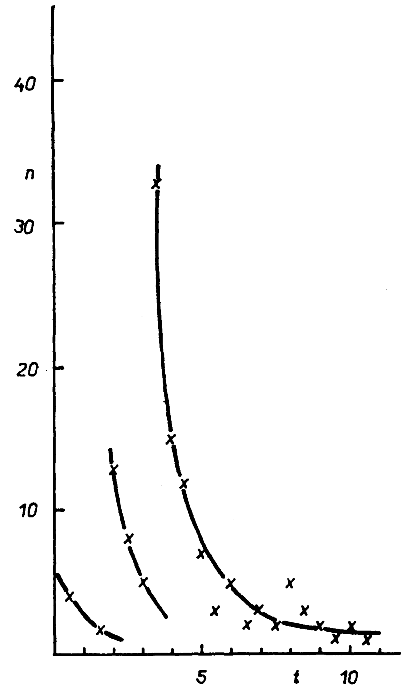

Fig. 12. Multiple earthquake sequence in Greece in the year 1953; the main shocks were of the magnitudes 6.2, 6.5, 6.7. The time interval between the main shocks was 2 days and $1^1/_4$ of a day

Another type occurring in Europe are "earthquake swarms". It is a group of shocks that does not contain any shock, which by its magnitude distinctly exceeds the others. The time duration of a swarm varies from several days up to several months. The seismic energy released in a time unit increases slowly with time to a peak and then it gradually falls [28]. The depth of shocks is usually small, the foci being in the earth's crust as a rule. Earthquake swarms are often encountered in volcanic regions [24]. The division of the number of shocks in a swarm according

Table 6. The properties of foreshocks

The number of foreshocks is smaller than the number of aftershocks [24].
The time interval, in which the foreshocks occur is several days at most and depends on the region and the magnitude of the main shock.
As a rule the strongest foreshock is weaker than the strongest aftershock. For Europe it was derived $M_0 - M_2 = -1.1 + 0.5\ M_0$, $M_1 - M_2 = -1.34 + 0.27\ M_0$, $M_1 - M_2 = -7.8 + 1.6\ M_1$ for $M_1 \geq 5$, $M_1 - M_2 = -2.3 + 0.5\ M_1$ for $M_1 < 5$, where M_0 is the magnitude of the main shock, M_1 is the magnitude of the strongest aftershock and M_2 is the magnitude of the strongest foreshock [24, 25]. From the above relations it follows that the difference between the magnitudes of the main shock and the magnitude of the strongest foreshock increases with the increasing magnitude of the main shock and that the difference between the magnitude of the strongest aftershock and the magnitude of the strongest foreshock increases with the increasing magnitude of the strongest aftershock.
The time interval between the strongest foreshock and the main shock is several hours up to several days. For Europe was derived the relation $\log \Delta t_2 = -1.73 + 0.39\ M_0$, where Δt_2 is the difference between the arrival time of the strongest foreshock and the arrival time of the main shock, M_0 is the magnitude of the main shock [24, 25]. From the above equation it follows that the time interval between the strongest foreshock and the main shock increases with the increasing magnitude of the main shock.
The distribution of the number of foreshocks according to magnitude is expressed by the relation $\log N = a - bM$, where a, b are the numerical parameters.

to magnitude is expressed by Gutenberg-Richter relation, the typical feature being a high value of parameter b, i.e. $b > 1$ [24], e.g. for the region of Kraslice it was computed $b = 1.31$. In Europe only weak shocks generally belong to earthquake swarms [24].

In Europe there are also pairs and triples of approximately equal shocks. A pair of shocks is regarded as a double shock if the shocks have a common epicentre and if the time interval between them is smaller than 20 to 25 days and if the difference between the magnitudes of shocks is smaller than 0.3 to 0.4 of the magnitude unit [24]. A triple is defined analogously. Both groups generally occur with weak shocks only [24].

It has been found that there is a regional division of types of earthquake sequences. As a matter of fact, in each region the prevailling type of earthquake

Table 7. The properties of multiple earthquake sequences

The difference between the magnitudes of the main shock is in 54% cases smaller than or equal to 0.3 of the magnitude unit, in 72% cases smaller than or equal to 0.4 of the magnitude unit and in 82% cases smaller than or equal to 0.5 of the magnitude unit [24, 25]. No regularity in the order of a weaker or stronger main shock was observed.
Between the magnitudes of the strongest and the second strongest main shock the following relation is valid for Europe $M_0 - M_0' = -0.15 + 0.10\,M_0$, where M_0 is the magnitude of the strongest main shock and M_0' is the magnitude of the second strongest main shock [24, 25].
Comparing the magnitude of the strongest aftershock M_1, which belongs to the strongest main shock M_0, with the second strongest main shock M_0' we obtain $\overline{M_0' - M_1} = 0.7$ of the magnitude unit [24, 25], which suggests that the magnitudes of the main shocks of multiple earthquake sequence distinctly differ by their size from the other shocks of the sequence.
The average time interval between the shocks of multiple earthquake sequence is 6 days. In 70% cases the time interval was smaller than 4 days [24, 25].

sequences can be determined for the selected range of magnitude. Figs. 13 and 14 list the prevailing types in the Mediterranean and adjacent regions.

Fig. 13 shows that with earthquakes of the magnitude $M \geq 6.0$, the type main shock and aftershocks prevails in most regions, only in Italy and Eastern Greece the type foreshocks, main shock and aftershocks prevails. Places where multiple earthquake sequences occur are indicated. It is mainly in Balkan area and Western Turkey. In regions where the considered three types of sequences occur a comparison of percentual representation of individual types was made. It was found that 50—60% shocks of the magnitude $M \geq 6.0$ in individual regions have aftershocks, further that 30—40% shocks of the magnitude $M \geq 6.0$ are the main shocks in multiple earthquake sequences and that 0–20% shocks of the magnitude $M \geq 6.0$ have foreshocks as well as aftershocks [24, 30]. It was found that the number of shocks having foreshocks and aftershocks and the number of shocks that are the main shocks in multiple earthquake sequences decrease with the decreasing magnitude and on the contrary, the number of shocks having only aftershocks increases with the decreasing magnitude [24, 30].

In Fig. 14 it can be seen that with earthquakes of the magnitude $5.5 \leq M < 6$ the type main shock and aftershocks prevails in most regions. In Eastern Turkey the most frequent are single shocks and in the second place the type main shock and aftershocks. However the ratio between these two groups is probably influenced by the incompleteness of the material in the field of weak earthquakes.

Mogi [11, 29] in Japan has also found regional distribution of the different types of earthquake sequences. Using his own results, he investigated the connection between spatial disturbance of the region and the type of sequence. He assumed the possibility of determining the degree of disturbance from the type of earthquake

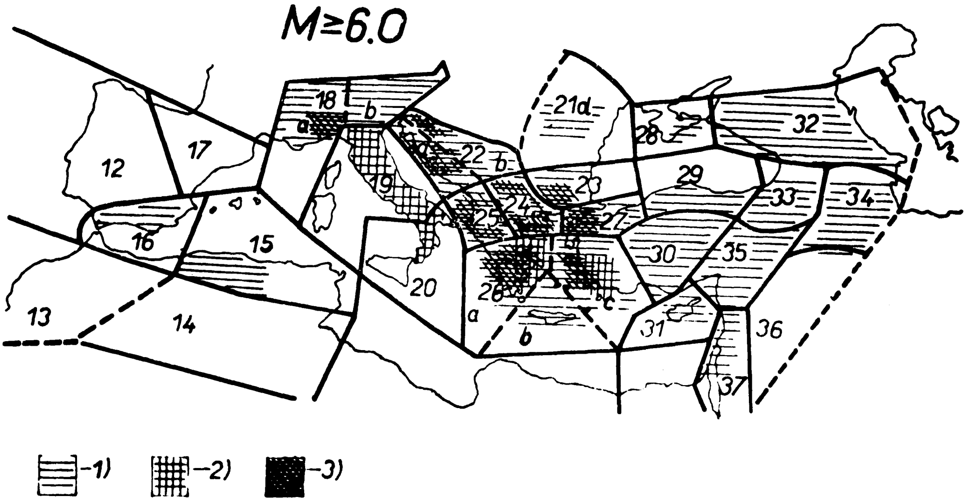

Fig. 13. Distribution of types of earthquake sequences in the Mediterranean; 1) – main shock and aftershocks, 2) – foreshocks, main shock and aftershocks, 3) – multiple earthquake sequences

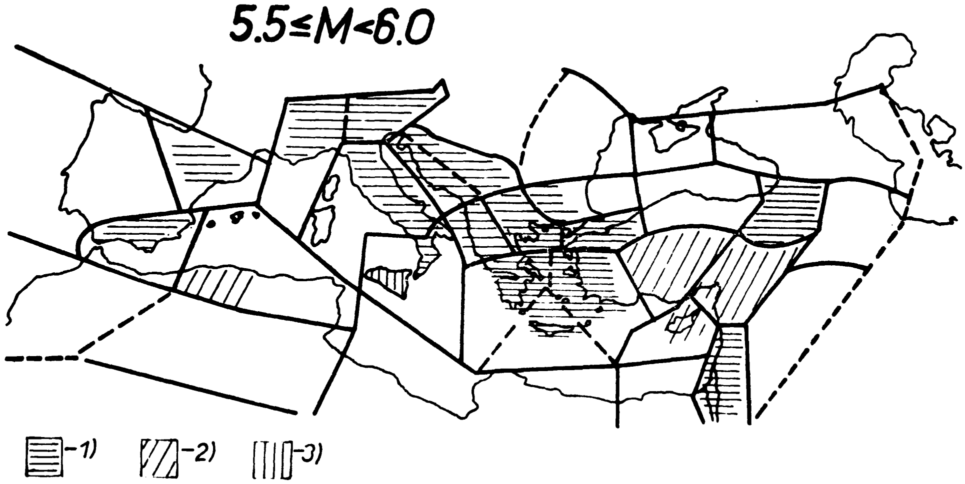

Fig. 14. Distribution of types of earthquake sequences in the Mediterranean; 1) – main shock and aftershocks, 2) – single shocks, 3) – earthquake swarms

sequence characteristic of the given region. There may be a connection between these two elements, however, it will not be so simple as imagined by Mogi since in most regions there are several types of earthquake sequences and moreover it was found in Europe that some types of earthquake sequences are typical of strong earthquakes and others of weak shocks.

2.6. *Migration of Earthquakes*

In determining the character of seismic activity it is necessary to solve the question whether the occurrence of earthquakes is arbitrary or whether it is subjected to some laws. Space-time tendencies in the occurrence of earthquakes are sought. In this connection we speak about the migration of earthquake foci. Under the term migration of earthquakes we understand a shift of foci in a certain region and at a certain time in one direction. Migration of foci was observed in Saint Andreas Fault, in the area of the Mariana Isles and the Isles of Tonga [31]. In Europe two sorts of earthquake migration were observed:

1. Migration of depth of strong intermediate earthquakes with time, i.e. in vertical plane [32];

2. Shift of epicentres in one direction, i.e. migration in horizontal plane [33].

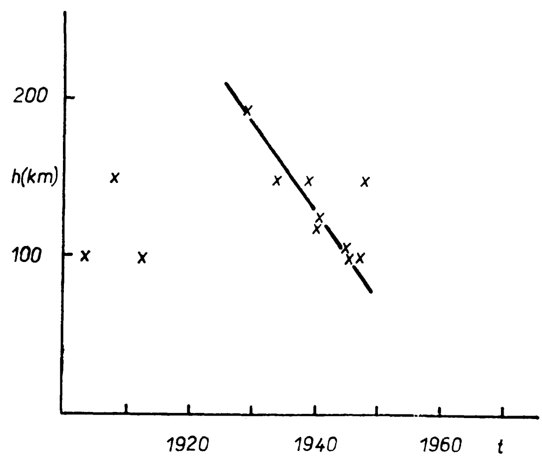

Fig. 15. Vrancea; time is marked on the horizontal axis and on the vertical axis is the focus depth in km

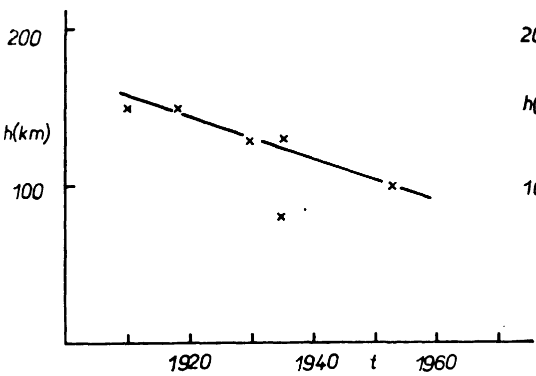

Fig. 16a.

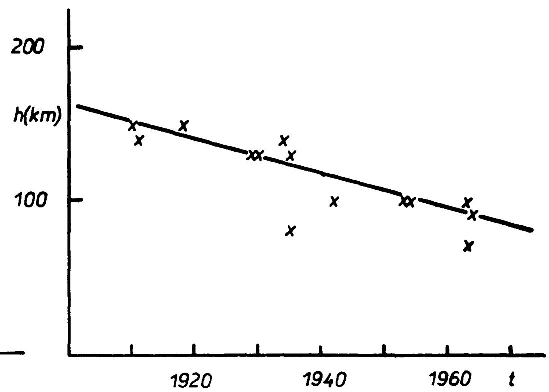

Fig. 16b.

Crete; time is marked on the horizontal axis and on the vertical axis is focus depth in km; a) – $m \geq 6$; b) – $m \geq 5$

In Europe the migration of foci in vertical plane was observed in the region Vrancea and the region of Crete, Figs. 15 and 16. From Fig. 15 it is evident that in the region of Vrancea the focus depth of shocks of the magnitude $m \geq 6$ was de-

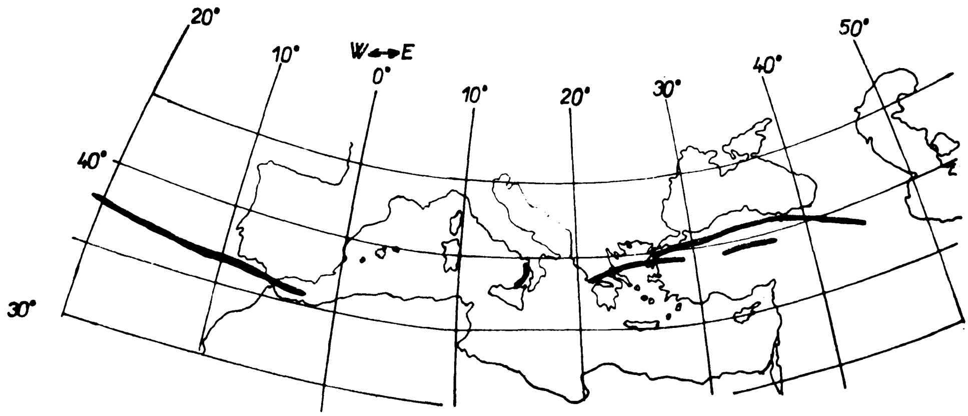

Fig. 17. Regions, in which migration of seismic activity in horizontal plane was observed

creasing in the period 1929–47 with the average velocity of migration in vertical plane 5.5 km per year. In Fig. 16 we can see that in the region of Crete the focus depth decreases with time. The decreasing trend is apparent when the earthquake of the magnitude $m \geq 6$ and the earthquake of the magnitude $m \geq 5$ are taken into consideration. The average annual velocity of migration in vertical plane is 1.3 km per year.

The observed decrease of depth of strong intermediate earthquakes with time evidences the fact that the cause of earthquakes shifts from the depth to the surface.

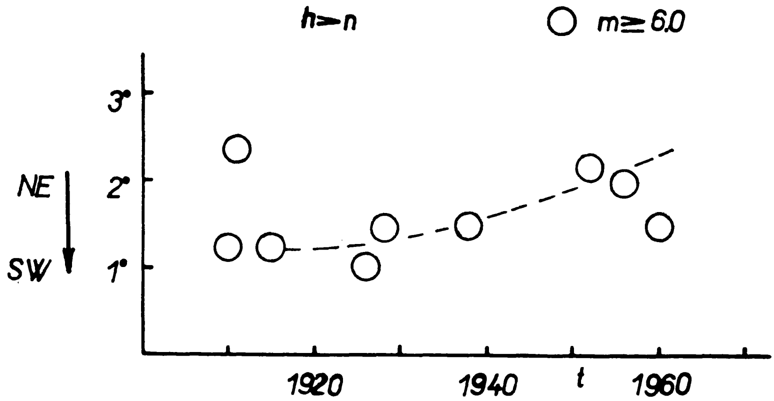

Fig. 18. Calabria; time is marked on the horizontal axis and on the vertical axis is the distance of epicentres in degrees measured from the southern limit of the line

There is an assumption that the shift of epicentres is connected with the process of magma. If this assumption is right there will be certain correlations between volcanic and seismic activities.

Migration of earthquakes in horizontal plane was observed in Europe along the lines depicted in Fig. 17. In Fig. 18 we can see that the epicentres of intermediate earthquakes shifted in the years 1910–60 in the zone passing through volcanic islands from Sicily to Southern Italy. Fig. 19 shows that the epicentres of earthquakes shift along the Azores Fault from the east to the west. The first shift with average annual migration velocity 0.45° per year was in the years 1910–45. The next shift has been taking place since the year 1955. Fig. 20 indicates that earthquake epicentres in region 30 shifted along the line parallel to the North-Anatolian Fault in the years 1920–42 from the west to the east and in the years 1909–20 from the east to the west; the average annual migration velocities were 0.27° per year and 0.63° per year. Fig. 21 suggests that it is rather difficult to find the activity trends in the North-Anatolian Fault. The simplest situation is in the central part where two shifts from the east to the west are apparent. On the edges 3–4 shifts from the east to the west can be dis-

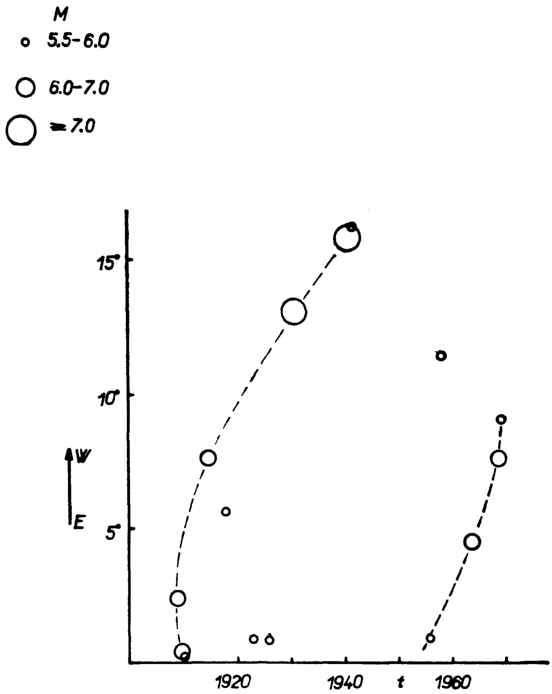

Fig. 19. Azores Fault; time is given on the horizontal axis and the distance of epicentres measured in degrees from the eastern limit of the line on the vertical axis

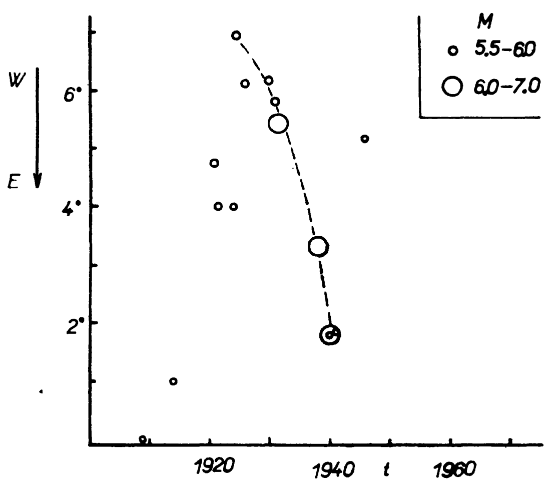

Fig. 20. Region 30; time is marked on the horizontal axis and on the vertical axis is the distance in degrees from the the eastern limit of the line

cerned from subjective views. A fairly distinct is the shift of epicentres of strong earthquakes with the magnitude $M \geq 7$. It is discutable whether this shift should be considered in the period 1929–53 as it is usually presented in literature, or whether it should be considered in the years 1929–62. In either possible variant are earthquakes of the magnitude $M \geq 7$, which do not belong to any distinct trend. The average annual migration velocity in the period 1929–53 for the earthquake of the magnitude $M \geq 7$ was 0.83° per year and the average annual migration velocity for the other variant of epicentre trend, i.e. for the period 1929–62 and for the earthquakes with the magnitude $M \geq 7$, was 0.45° per year.

The earthquakes whose epicentres belong to one arise probably due to one pressure system and the origin of a strong earthquake in one place affects the origin of a strong earthquake in another place.

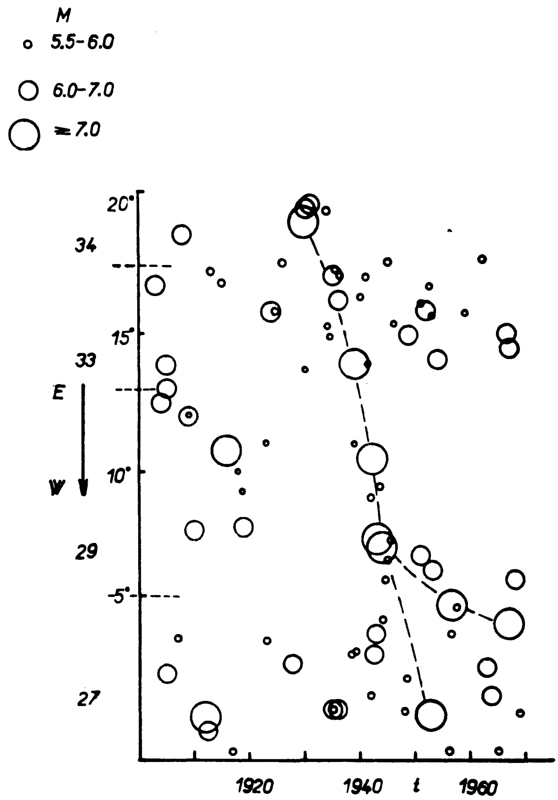

Fig. 21. The North-Anatolian Fault; time is marked on the horizontal axis and on the vertical axis is the distance in degrees from the western limit of the line

3. Seismic Activity on the Territory of Czechoslovakia

In Czechoslovakia there do not occur earthquakes of disastrous effects. Only a part of our country is afflicted by shocks, damage arising very seldom. The territory of Czechoslovakia is made up of two geologically quite different units, the Bohemian Massif and the West Carpathians, which also substantially differ by the intensity as well as the character of seismic activity.

In the western part the likely cause of shocks is the pressure of the Alps arc on the old floe of the Bohemian Massif, into which earthquakes from the surroundings also penetrate. In the eastern part lies the source of seismic phenomena in the actual tectonics of a young mountain system the Carpathians. Also earthquakes from the neighbouring epicentres, the Eastern Alps, the Carpathian Basin and the

Hungarian Basin, greatly contribute to the picture of seismic activity in Czechoslovakia.

The seismic characteristics of the Bohemian Massif is affected on the one hand by earthquakes whose epicentres lie on the territory of the Bohemian Massif [34] and on the other hand earthquakes from the Eastern Alps and Germany. The earthquakes from the Eastern Alps, possibly from the Alps foreland are transferred exceptionally strongly northwards to Bohemia and the western part of Moravia whereas in the direction to the Carpathian system they are strongly damped [35, 36]. The shocks with the epicentre intensity about 8 degree M.C.S. scale manifest themselves macroseismically as far as Dresden, their macroseismic field is of pearlike form, and the effects of these shocks are felt more distinctly in mobile zones [35, 36].

The shock occurring on the territory of Bohemia and Moravia are generally weak, the strongest are of the magnitude $M = 4.9$ and they are usually of tectonic origin. The shocks are as a rule in groups of two types. In the boundary mountain regions, mainly Smrčiny, Krušnohoří and Český Les, there occur mostly earthquake swarms lasting usually several months and sometimes there appear about one hundred shocks in a day. In this century there were great earthquake swarms in the years 1903, 1908, 1962. In the region of Trutnov and Náchod where the shocks are connected with the Krkonoše Fault there usually occur groups of the type main shock and aftershocks. For the period 1871–1970 the relation $\log N = 7.07 - 1.30\,M$ for $M > 3$ was computed by the maximum likelihood method, where N is the simple frequency. In the computation, classes with the step 0.5 of the magnitude unit were considered. The high value of the graph slope is caused mainly by the role of the Kraslice region, where earthquake swarms occur, for which a high value of parameter b is typical.

The West Carpathians are seismically more active than the Bohemian Massif. Seismic activity appears particularly in the inner parts of the mountain range. As a rule, the epicentre depth is 5 km and with stronger ones 10–20 km. The shocks occur mainly in the groups of the type main shock and aftershocks. The strongest shock in the year 1763 was of the intensity 10° of M.C.S. scale, which corresponds to the magnitude $M = 6.3$. Following this shock there were weaker shocks for a number of years in the whole afflicted area, i.e. in the surroundings of Komárno [37]. The earthquake epicentres are mainly in the Small Carpathians, in the surroundings of river Váh, the neighbourhood of Banská Bystrica and in Eastern Slovakia [36]. For the period 1871–1970 the relation $\log N = 3.89 - 0.64\,M$ for $M > 4$ was computed by the maximum likelihood method, where N is the simple frequency. In the computation, classes with the step 0.5 of the magnitude unit were considered. Comparing this relation with the same relation for the Bohemian Massif, we can see that the numerical values of the parameters of both regions differ substantially as to the magnitude. This evidences the fact that the character of seismic activity in these two regions is greatly different.

4. Conclusion

The character od seismic activity in individual partial regions is rather different. These regions differ from each other by different values of the parameters of the magnitude-frequency relation, the number of earthquakes, the value of the greatest earthquake that can be expected in one or another region. Also the types of earthquake sequences occurring in individual regions are different. In some regions certain trends of seismic activity, i.e. migration in horizontal and vertical planes were also observed.

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