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Earthquake Pattern in Central Europe

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The present paper deals with the study of earthquakes in the ČSFR and in the whole Central Europe. It gives a description of the typical character of earthquake activity of a region with low seismicity. Attention is mainly concentrated to the regions: the boundary between the Bohemian Massif and the Western Carpathians, Mur-Muerz-Leitha, Aš-Skalná-Kraslice-Bad Elster-Selb, Vrancea, because the data sets of these regions are comprehensive. It contains a description of the seismicity in individual focal regions, qualitative and in some cases also quantitative characteristics. The differences in earthquake regimes are accounted for by the differences in the structures of regions and in focal processes.

Práce se zabývá studiem zemětřesení v ČSFR a ve střední Evropě. Hlavní pozornost je soustředěna na oblast styku Českého masívu a Západních Karpat, Východní Alpy (oblast Mur-Muerz-Leitha), oblasti Aš-Skalná-Kraslice-Bad Elster-Selb a Vrancea. Údaje o zemětřeseních v těchto oblastech tvoří obsažné soubory, dovolující určit statistické vlastnosti zemětřesení a zemětřesných režimů.

Specifikou sledované oblasti je to, že se jedná o oblast s nízkou zemětřesnou činností. Proto je práce založena i na analýze historických zemětřesení, pro něž máme k dispozici data makroseismická a na analýze současných zemětřesení, pro něž máme data přístrojová i makroseismická.

Práce shrnuje získané statistické zákonitosti a diskutuje výsledky studia rozložení zemětřesení, makroseismických polí, mechanismů zemětřesení, Benioffových grafů, časoprostorových závislostí, apod. s cílem najít fyzikální a geologická kritéria seismicity v konkrétních oblastech.

Strategie práce spočívá v tom, že údaje o jednotlivých zemětřeseních, získané stejným přístupem k výchozím informacím, jsou zpracovány stejnou metodou. Pozornost je zaměřena, jak na studium jevů, tvořících většinu, tak na doložené jevy anomální. Získané výsledky jsou příspěvkem k řešení hlavních seismologických úloh, jako je předpověď zemětřesení či odhad zemětřesného ohrožení konkrétní lokality.

Introduction

In earthquakes, the complex problems of the possibility of predicting them and determining the seismic risk of a specific locality from both the practical and scientific points of view are of paramount interest to us. The prerequisite is the study of earthquakes and the regularities of their space-and-time distribution,

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and last but not least, also the study of genetic connections between the foci of strong and weak earthquakes with horizontal and vertical inhomogeneities of the geological medium in the Earth's crust and the upper mantle.

An earthquake is a phenomenon of a physical origin. It is generated by a sudden release of mechanical energy in the Earth's interior. Each earthquake is a individual to be characterized by the geographic coordinates of the focus, the focal depth, the origin time, the size, the orientation of the system of forces acting in the focus, the prevailing force multipole, the stress drop due to a disturbance, the size of irreversible deformation of the focus and by its time course, the shape of the disturbed region and by its size as well as by the distribution of macroseismic effects. Each earthquake originates as a result of certain physical causes, however, its origin is also connected with a number of other conditions which because of their pecularities and great variety are the sources of random features of the process.

Earthquakes are the most distinct manifestations of tectonic activity. They originate under specific conditions that vary in dependence on the tectonic zone. Their generation is not a stationary process either in time or space. It is a consequence of long-term tectonic processes, whose rate is very slow compared with human life, i.e. with our observation possibilities. The entire tectonic process, a manifestation of which are also earthquakes, does not consist in the movement of not only one block along a fault, but the blocks in all the surroundings start moving due to the new pressure situation. This gives rise to the formation of cracks and movements along faults as well as to the deformation of a broader vicinity. Tectonic movements are not invariable in time, there are so-called rhythms of tectonic movements lasting for several centuries (Chigarev 1980). In our deliberations, therefore, we have to start from the fact that the seismic activity of the regions studied by us changes with time. For instance, simultaneous quietening of the seismic activity, a so-called "gap", in some places need not necessarily mean they are aseismic, which is quite evident from the time – longest observation series in the Eastern Mediterranean, China and in the Southern Alps, which point out the existence of periods of quiescence and periods of high seismic activity lasting several centuries.

The present philosophy of earthquake occurrence presumes that an earthquake in a particular region is being prepared for a certain time. In the course of its preparation, physical and chemical properties of the geological medium change. The changes in properties manifest themselves as anomalies of measurable parameters. We regard these anomalies as symptoms (precursors) of an imminent earthquake. On their basis attempts at earthquake prediction in concrete regions are made (Procházková 1989). According to works (e.g. Matsamura 1984, Zhadin 1984, Mc Nally 1982) changes of the seismicity pattern in space and time belong to the seismological precursors. Therefore, the object of this work is the study of the earthquake occurrence pattern in Central Europe. In order to prevent material

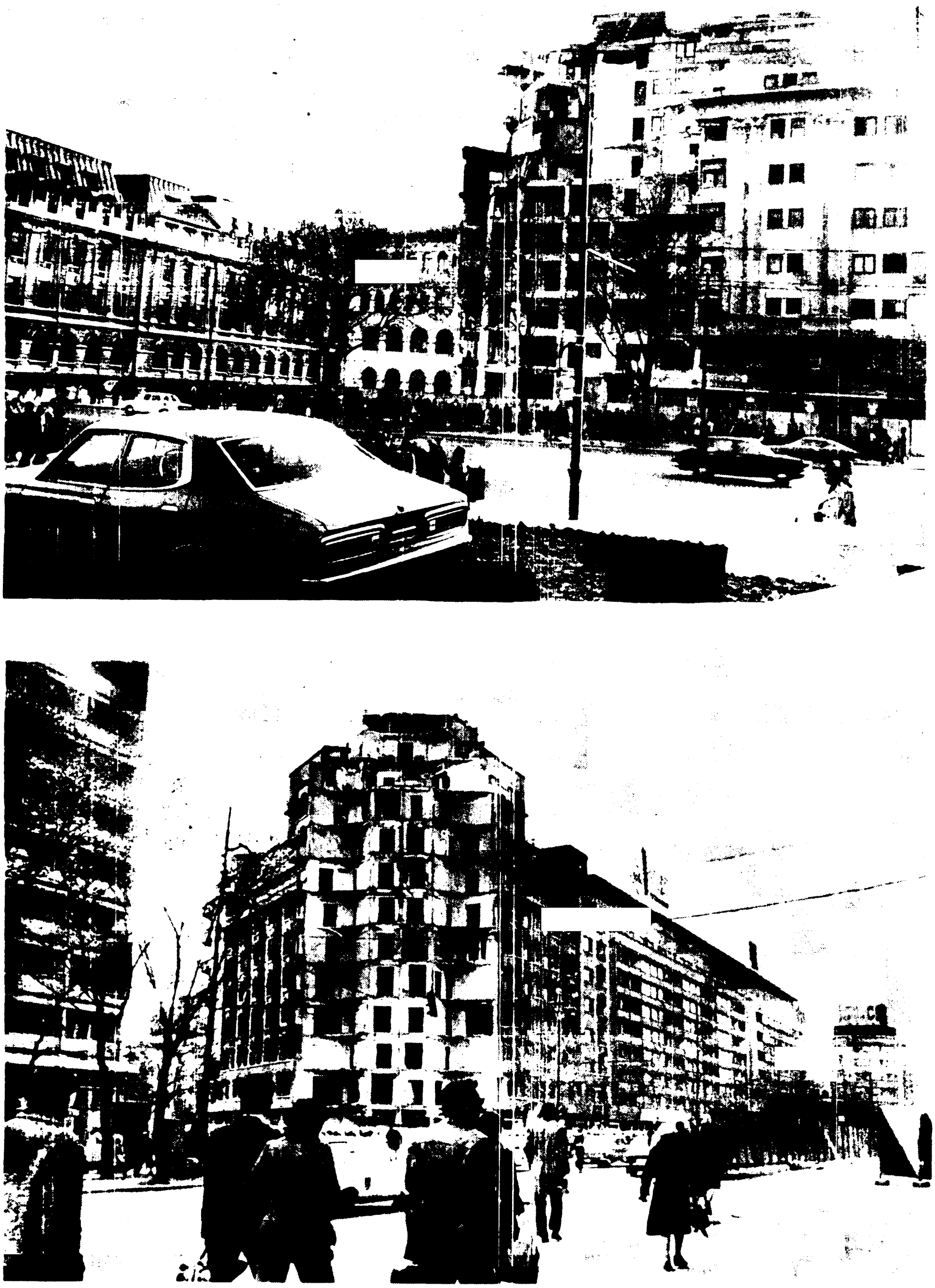

Fig. 1a

The material damages caused by the earthquake of March 4, 1977 in Vrancea in Bucuresti (Romania).

Fig. 1b

The material damages caused by the earthquake of September 3, 1978 in Swabian Jura in Albstadt (FRG).

Fig. 1c

The material damages caused by the earthquake of December 21, 1985 in Western Bohemia in Dolní Žandov (ČSFR).

damage (Fig. 1) and losses human lives, we estimate the seismic hazard of different localities. In way, the earthquake hazard calculation can be viewed as a kind of long-term earthquake prediction. During the last two or three decades seismologists have been confronted with an increasing number of requests to evaluate seismic hazard for the design of important structures and for urban and disaster emergency planning. The calculation creates a specific problem. For the determination of the real seismic hazard of a given good knowledge of the space-and-time pattern of earthquakes and of the space distribution of earthquake effects is necessary.

The present work studies earthquakes in Czechoslovakia and whole Central Europe. Its results are to be instrumental in the solution of the main problems connected with the safety of important structures on the territory of Czechoslovakia. That is why it deals in detail with focal regions in the territory of Czechoslovakia and its close vicinity, more distant focal regions are marginal to it.

The work does not specially deal with the study of seismic activity in mining districts where man's intervention into the nature can be presumed to have made a contribution to the origin of earthquakes. (Under displacement of masses on the Earth's surface or in its close vicinity the equilibrium of a mountain massif is disturbed. Additional stresses are generated, which, together with other changes in the medium physical parameters, may act as a trigger of stronger shocks in the regions where sufficient stress has accumulated due to tectonic processes).

2. Strategy of research

A condition of an all – round recognition of a natural phenomenon and thus also of an earthquake, is its complex analysis. One of the forms of the analysis is also the classification into classes according to certain features (focal depth, size, etc.). The analysis of a developing process makes it possible to find the substantial features of the process, to single out its different stages, contradictory tendencies, etc. In the process of analytical activity, our ideas follow the path from a complicated matter to a simple one, from an incidental matter to a necessary one, from variety to identify and unity. From the dialectic viewpoint, synthetic activity complements the analysis and forms indestructible unity with it. That is why phenomena, properties and relationships established by analysis are unified into a whole.

Investigations into earthquakes of a particular region are regarded as a long--term dialectic process. New events are being constantly added and the earlier ones are processed from completely novel views. It has turned out, for example, that at the present time it is not sufficient to study only strong earthquakes. It is true that weak earthquakes require much more demanding work in collecting data, but they provide us with information on e.g. the stress being accumulated in a given region, which may result in a strong earthquake in the future.

The main principle of seismological research is a complex uniform study of earthquakes and the seismic activity in the area under investigation, i.e. considering all available seismological information and a possible use of some information obtained in other geophysical branches and in geodetical surveys, making their physical interpretation and assessment from different viewpoints.

The data on individual earthquakes obtained by the same approach to the initial information have to be processed by a uniform method. By violating this principle, in many cases we may get formal differences that are not substantiated physically (Procházková 1972). The application of uniform methodology allows establishing common and different properties of single earthquakes as well as of individual regions in respect of quantitative and qualitative characteristics of seismic regimes. Attention must be directed towards both the study of events that form the majority and fit statistical laws, and events that distinctly differ from these used laws. In case that anomalous events (such as e.g. different duration time of aftershocks, prominently weak or prominently strong aftershocks, a great difference between the size of the main shock and that of the strongest aftershocks, etc.) are well documented, it is necessary to investigate the causes of their differences and consequently, obtain new findings on earthquake occurrence. Although the causes of all differences have not been identified as yet, establishing their existence is a valuable contribution to the knowledge of objective laws and regularities.

In studying the space and time regularities in earthquake occurrence, first of all we have to single out the region in such a way as to form a seismotectonic unit, i.e. the region characterized by the same process of earthquake generation and by the same mechanical properties. The statistical methods based on the determination of places that correspond to inflexion points on the summation curves constructed in several azimuths may be responsible for a wrong approximation of the region boundary to a place of seismic activity quiescence or "gap", which in time is filled with an earthquake occurrence. Neither can earthquake regions be singled out according to geological symptoms, as applied e.g. in works of Gelfand et al. (1972, 1973), because it is not always objective and realistic as shown in the work by Nikolaev and Nikolaev (1979); there exist regions with the same geological features but quite a different nature of seismic activity. For this reason, it is useful to define the boundaries of regions as separating regions with different space-and -time regularities; we proceed from small clusters of foci connected with the movements along one fault or a system of parallel faults towards larger units. First of all we must determine seismoactive faults. In the recent time, seismoactive faults are those that are connected with foci of historical as well as present earthquakes. The attribution of an earthquake focus to a fault is determined by the mutual position of a focus and a fault, and also by the earthquake mechanisms (Procházková et al. 1986).

In order to tudy seismicity, it is necessary first to prepare homogeneous data sets obtained by a uniform approach to macroseismic and instrumental information, i.e. the earthquake catalogues. They present relevant information on earthquake parameters and earthquake effects in a concise form. They are completed and improved all the time in given time intervals they are homogeneous only from a given value of epicentral intensity or magnitude. The main difficulty we are confronted with in preparing a catalogue is connected with the evaluation of reports of historical earthquakes that occurred some hundred years ago. These earthquakes are often only fragmentarily described in chronicles and archive documents and it is necessary to take into account that the sizes of these shocks can often be overestimated. It is possible to assume that the chroniclers only recorded the most severe damage. Due to the brevity of these reports the overestimation of intensities of historical earthquakes is logical. The impossibility of a detailed analysis reduces the intensity accuracy and causes rather overestimation than underestimation. In spite of these influences which obviously distort the knowledge concerning earthquakes and the earthquake activity, the macroseismic observations provide important and for the time being the only long-term information on the seismicity of individual regions.

3. Methods of data processing

A method in the most general sense is a systematic organization of scientific activity. The bases of all gnoseological methods involve objective laws of the reality. One of the methods of building scientific gnosis is the deduction method (deriving the partial peculiar from the general), which is inseparably connected with the induction method (progress from particulars to a general conclusion). The deduction method is applied if empirical material has been amassed and theoretically expounded. The purpose is to introduce a certain system for all the consequences ensuing from the given assumptions to be derived exactly. In the course of this process new findings are obtained.

In studies the following methods are generally applied:

a) Establishing individual facts and a system of obtaining primary data.
b) Selective investigations, whose object is longer-term verification of the facts observed.
c) Methods of processing primary data (description and classification, generalization, system analysis, etc.).

Apart from logical procedures (analysis and synthesis), the search for statistical regularities is of great importance in data processing. Statistical as well as dynamic (function) regularities are forms of the manifestation of regularities of the causal relation of phenomena. The dynamic regularity is such a form of the causal relation, under which the given state of the system unambiguously determines all its next states. Statistical regularity is a form of the causal relation, under which the given state of the system determines all its next states, not unambiguously but with a probability as an objective measure of the possibilities that the changes already prepared in the past will be realized. Strictly speaking, each regularity is statistical since no system is perfectly isolated being in mutual interaction with the environs. By all means, we choose such methods of collecting and processing primary data that ensure objective information.

The macroseismic effects of earthquakes depend on the earthquake size, depth, mechanism, on the one hand, and on the physical properties of the medium through which the seismic waves propagate, on the other. The distribution of macroseismic effects of earthquakes is represented by isoseismal maps. Of greatest value are the maps that comprise individual observations as they give the user the possibility to judge the interpolatioon of isoseismals and possibly a basis for his own interpolation (Procházková, Kárník 1978). The method of determining earthquake parameters on the basis of macroseismic data is described e.g. in (Procházková 1981, 1984, Procházková, Dudek 1982).

Methods of processing seismograms in the analogue form recorded on paper, magnetic tape, or in the digital form are the subject of a lot of works, e.g. Willmore (1979), Båth (1981), Brune (1968). It is the question of determining arrivals of seismic waves, focal position, magnitude, the earthquake mechanism and the source parameters of earthquakes, such as the seismic moment, focal dimensions, stress drop and the relative displacement of blocks along a fault.

Seismological maps are the graphic representation of the distribution of values of a quantity, characterizing earthquake occurrence in time and space in a particular region and a particular time interval. There are maps of epicenters, maps of the maximum observed intensities, maps of the seismic activity, etc.

The map of epicentres constructed to show the space earthquake distribution is a discrete map, each epicenter being represented by a point. In order to express quantitatively the earthquake size, to which a focus is appurtenant, we introduce various symbols for the magnitudes or epicentral intensities, e.g. circles of different radii. If the differences in focal depths are great, the shocks must be also classified according to their depths.

The methodology of constructing maps of the maximum observed intensities is described e.g. in (Procházková 1976a, and 1984). Since in the historical times inhabitation was not even, and since organized data collection has only been made in the recent period, data on intensity distribution are missing in earlier earthquakes. The unevenness in the surface distribution of macroseismic data can be systematically removed only after setting up a homogeneous network of macroseismic effects (organized e.g. through the authorities of State Administration, police, post offices, schools, etc.). Maps of the maximum observed intensities constitute the simplest map of seismic zoning.

The empirical function which describes the distribution of the earthquakes number according to their size, is of basic importance in statistical investigations of seismicity. A survey of the most frequently used functions is contained e.g. in

(Procházková 1976b). The frequently applied relations $\log N = a - bM$, or $\log N = a' - b'I_0$, where N is the number of earthquakes, M the magnitude, I_0 the epicentral intensity, and a, b, a', b' the numerical parameters, are only valid in a certain interval of magnitudes (M_1, M_2) or of intensities (I_{01}, I_{02}). It is obvious that generally the frequency distribution must be limited on either side, i.e. in the given volume there must exist the smallest and the largest possible earthquakes, defined by values M_{min} and M_{max}; $(M_1, M_2) \in (M_{min}, M_{max})$. It is difficult to determine M_{min} for particular focal regions, for the data on weak shocks are not homogeneous, and neither do the sensitive instruments used recently record all shocks because many of them lie below the level of permanent disturbing seismic noise, often of man-made origin. It is equally difficult to determine M_{max} because in the particular region, the largest possible earthquake need not have been manifest during the historical period of observation. As a matter of fact, it was innitially presumed that it was easy to be determined from the curvature of the frequency graph in the domain of the largest magnitudes. But the results of studies have shown that there are few well documented curvatures within the interval (M_2, M_{max}), and moreover, these curvatures may only be the result of "saturation" of the magnitude scale, which ceases to be an adequate measure of an earthquake size in the domain of high seismic energies. Actually, the standard magnitude scale is based on the use of amplitudes of surface seismic waves with period $T = 20\text{ s} \pm 2\text{ s}$, in stronger earthquakes, however, the main part of energy is carried by seismic waves with $T \gg 20$ s.

In seismology, under the term cumulative frequency $N_c(M)$ we understand the number of earthquakes with a magnitude greater than or equal to M. The summation curve begins in large M's and in the coordinates $[M, \log N_c(M)]$ it approaches a straight line, and therefore, it is usually substituted by a straight line: $\log N_c(M) = e - fM$, where e, f are the numerical parameters. The relation between the cumulative frequency and the simple frequency is expressed by the equation $N_c(M_k) = \sum_{i=k}^{s} N(M_i)$, where $k = 1, 2, \ldots, s$; s is the number of different magnitude values aligned in a growing sequence $M_1, M_2, \ldots, M_s$. Our theoretical study and practical calculations (Procházková 1972) have demonstrated that parameters a, b and e, f cannot be interchanged. Analogically, it holds for $N_c(I_0)$.

Parameters a, b from the magnitude – frequency relation are of a physical significance. The value of parameter a gives the level of seismic activity in a given region, and is equal to the logarithm of the number of shocks with magnitude $M = 0$. The higher the value, the higher the activity. The numerical values of parameter a also depend on the length of the time interval and on the size of the focal region. Parameter b represents the slope of graph $\log N(M)$. Its numerical value determines the relation between the number of strong earthquakes and the number of weaker ones.

The object of studies of the time course of the seismic regime is to identify specific features that are signs of an approaching earthquake disaster. Investigating this course means investigating the change of seismicity parameters with time. We usually depict these changes graphically. To this end we most frequently use Benioff graphs which represent the summation of $E^{0.5}$ values, E being the seismic energy radiated from the focus. It is the dependence $\sum_i E^{0.5} i = f(t)$, where E_i is the seismic energy released under individual earthquakes, t being the time. Benioff graphs depicting the process of energy release with time represent the process of deformation release with time only if the relation between total deformation and released energy can be written in the form $\varepsilon = \sum_i k_D E_i^{0.5}$, where k_D is a constant (Procházková 1976b). However, even in the case of the first approximation when the theory of elasticity is applied, it follows that $k_D = [2/(p\mu V_i)]^{0.5}$, where μ is the torsion modulus, p is the coefficient of the conversion of elastic energy into the energy of seismic waves, and V_i is the focus volume. The focus volume size depends on the earthquake size (e.g. Båth 1981) and on the earthquake type (low stress drop or high stress drop – e.g. Procházková 1983, 1984).

We apply Benioff graphs to classifying active and quiescent periods in a region from the point of view of seismicity. In active periods their slope is great as opposed to a very small slope in quiescent periods. With their help it is possible to single out the time periods, in which accumulated energy was released in the form of one or several strong shocks, and the periods when accumulated energy was released in the form of a great number of weaker shocks. Decisive influence on the pattern of these graphs exerted by strong earthquakes, weaker ones are hardly manifest in them. By means of Benioff graphs single active systems can be compared. The energetic regime of a seismic region is dependent on the frequency of strong earthquakes.

The dependence of the cumulative seismic moment on time $\sum_i M_{oi} = f(t)$ has been lately applied to characterizing the time regime of regions. The cumulative seismic moment represents the total slip of the fault region, i.e. the displacement of blocks along the fault. Periods with low seismicty are distinguished by a small average annual slip and vice versa.

The size of the largest possible earthquake in a region depends on the size of tectonic forces on the one hand, and on the other, on the properties of the medium affected by tectonic forces. It is most frequently determined from the oscillations of the Benioff graph, from the curvature of graph $N(M)$ or $N(I_0)$, by means of correlating the maximum observed earthquake with the level of seismicity, by the theory of extreme values or by so-called geodynamic factors (e.g. works Borisov, Reisner, Sholpo 1975, Riznichenko 1962, Schenková, Kárník 1974).

Earthquakes are not an isolated phenomenon. They tend to cluster in time and space. There originate groups of shocks that differ from one another by their structure and properties, Fig. 2. The group main shock – aftershocks is such a group in which the first shock, the main one, is much stronger than the subsequent shocks referred to as aftershocks. Foreshocks – main shock – after-

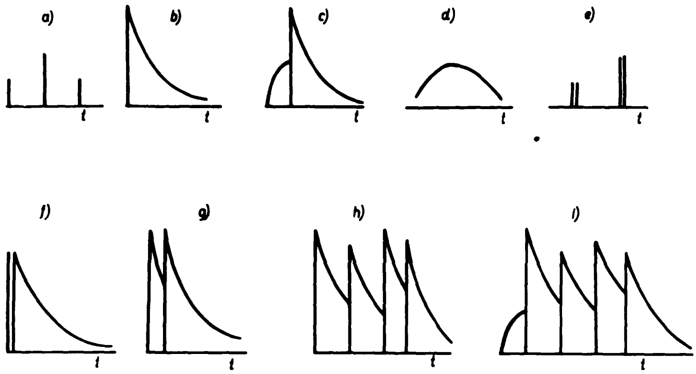

Fig. 2

Types of earthquake sequences; 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 shocks,
f) – i) multiple earthquake sequences.

shocks is a group in which there are weak shocks before and after the strongest shock. Multiple shock groups conttain more approximately equal by strong shocks and some weaker shocks that follow each of the strong shocks and have the properties of aftershocks. An earthquake swarm is a group of shocks that lacks a shock that would distinctly surpass the others by its size. As a rule, earthquake swarms only consist of relatively weaker shocks. The properties of earthquake groups are described e.g. in (Procházková 1976, 1984, 1987a, b, 1990b).

By the migration of earthquake foci we understand a shift of foci in time in one direction in a region and in a certain period. We often observe several shifts of foci in the same direction; one shift is called the migration cycle. Migration of foci in the vertical as well as horizontal planes would be observed. In order to establish migrations of foci, we construct time-and-space graphs. In the direction, in which earthquake foci are orientated we put an axis and project the foci of individual earthquakes onto it, and construct the dependence of the foci positions on time.

The process of the origin of earthquakes is the result of the mutual action of a great number of factors and it is a very intricate one. At the present time, we already have a big body of findings on the connections of geological and seismological data, and the methods of studying these connections are being improved further. The method of searching for seismotectonic connections and its assumptions (Procházková et al. 1986) is based on the fact that there are a number of uncertainties, such as the exact fault position, the fault dip, the width of the fault zone, the focus position, etc. We make a mutual attribution of an earthquake focus and a fault if:

- the earthquake epicentre belongs to fault zone ± 5 km;
- the elongation of isoseismals in the epicentral zone or the direction of the slip (determined from the earthquake mechanism) and the direction of the fault are almost identical ($\pm 20°$);
- there is geological evidence on the neotectonic activity of the fault.

All findings are defined, refined and verified by practice. They cannot be conclusively verified in the course of an individual, isolated, specially performed investigation. One of the methods acquiring scientific knowledge, in general, is the construction of concrete models of a particular object. Between the model and the object there must be an analogy. It either consists in conformable characteristics of the model and the object, or in conformable functions effected by the model as well as the object, or in the identity of a mathematical description of the "behaviour" of the object and its model. That is why by comparing the parameters and the characteristic features of individual earthquakes we construct models that reflect the basic characteristic common properties of a great majority of earthquakes in a particular focal region (so-called seismotectonic characteristics of focal regions), and naturally we also study the properties by which single earthquakes in the region differ from each other. Acquisition of new results enables us to constantly improve the model and make it more realistic.

4. Description of the region under investigation

From the geological point of view, the study area, Fig. 3, is mainly formed by the Hercynides and Alpides. Central European Hercynides lie mostly on the outer margin of the Alpine — Carpathian foredeep. Their principal outcrops are the Bohemian Massif, Black Forest, Vosges, the Rhine slaty mountain range. They are hidden below the platform sediments between Munich and Berlin, and partly between the Oder and Vistula lineaments. Central European Alpides comprise the region south of the Alpine — Carpathian foredeep, which runs in the rim of the Swiss Alps between Bern and Zurich, continues along the Danube in Austria as far as the Czechoslovak territory. Here, it continues from Znojmo to Ostrava, and it terminates arclike in the east and south rims of the Eastern Carpathians near the Danube. In Central Europe, we divide the Alpides into the Alps (Western, Eastern, Southern), the Carpathians (Western, Eastern, Southern) and the Dinarides. Part of the Alpide region are also central "median" massifs, e.g. the Pannonian Massif. This area is thus composed of several different geological units of the first order of different age and different histories of the geological development, which is reflected in the structure and thickness of the Earth's crust and in the differences of geophysical fields.

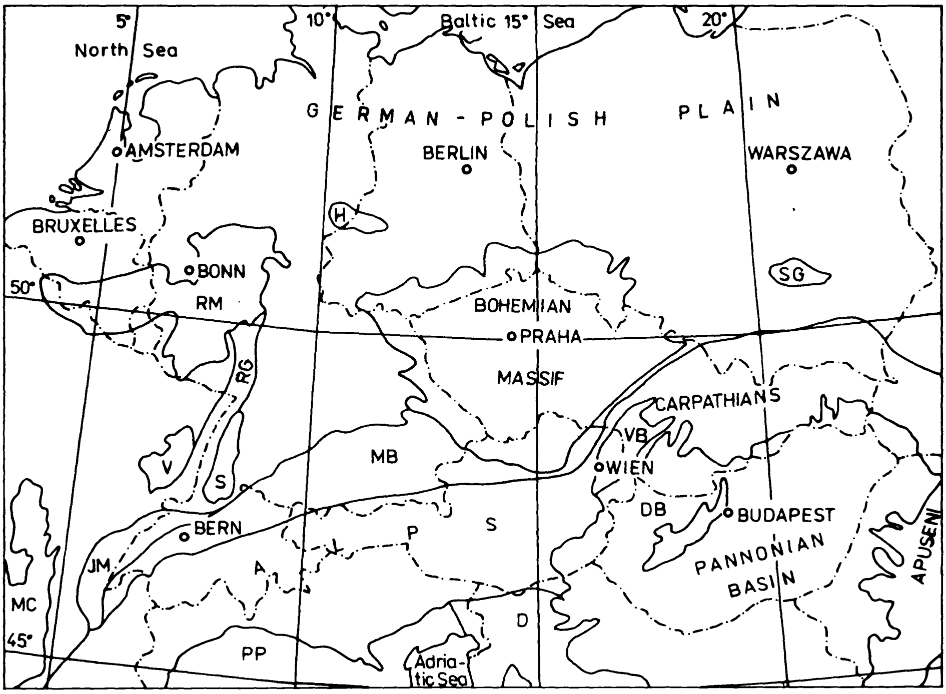

Fig. 3

The investigated territory and its principal orographic and geological units (state boundaries marked by dotted line). Abbreviations:
D — Dinarides, DB — Danube Basin, H — Harz Mts, JM — Jura Mts, MB — Molasse Basin, MC — Massif Central, PP — Po Plain, RG — Rhine Graben, RM — Rhine Mts, S — Schwarzwald Mts, SG — Holy Cross Mts, Vosges Mts.

The development in the course of the Upper Tertiary shaped the tectonic skeleton of the present Central European relief. The Upper Tertiary foundation has the relief of both the Alps, the Carpathians, the block mountains of the Bohemian Massif and its surroundings (Krkonoše, Šumava, Krušné hory Mts, Harz, etc.) and the large depression inside the Alpides (e.g. Pannonian Basin, Transylvanian Basin) and on the epi-Variscan Platform (molasse basin in the foreground of the Alps, the Rhine graben, etc.).

According to the current assumptions, the events that produced the present orographic units mentioned above, involve tectonic processes excited by the continuing collision between the continental block of Africa (carried towards the north with respect to Europe over 200 Ma by the ancient African lithospheric plate at a generally stable rate of about 25 mm/year; e.g. Roth 1987) and the Proterozoic continental core of Europe (Fennosarmatia), which has hardly changed its position relative to the Earth's rotation axis (in contrast to Africa) since the beginning of the Tertiary (Krs 1982).

From the geohistorical viewpoint of the Alpine development stage, the Hercynian – Alpine collision zone (comprising Central Europe) is formed of two regions which mutually differ by the intensity of their Alpine (Tertiary) deformati-

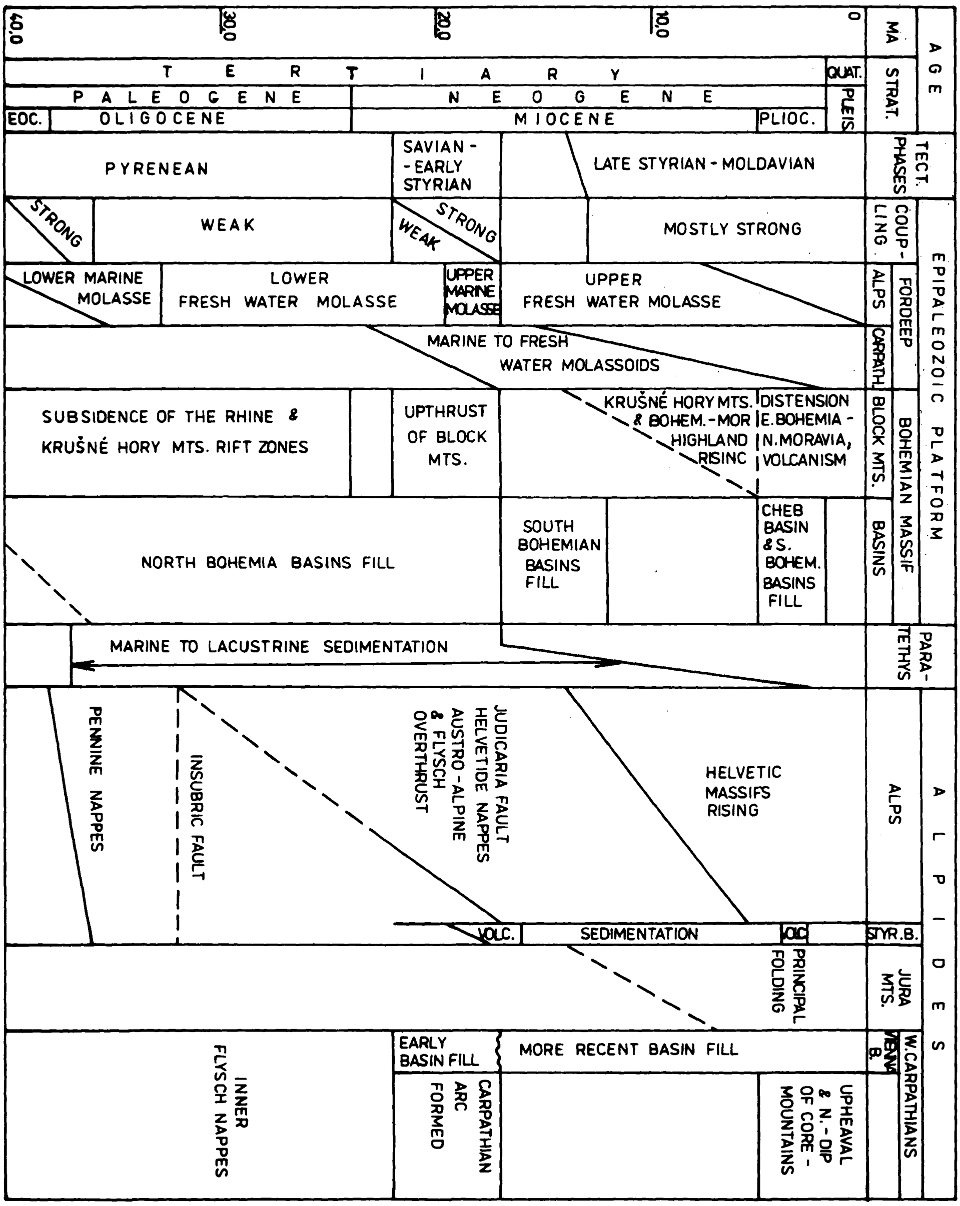

TABLE 1
Chronological model of neotectonic movements

on. The southern, wider belt of the collision zone is formed by the Mediterranean branch of the Alpides (average width about 1200 km). Here, Tertiary structures dominate over shreds of the earlier structure (Hercynian and possibly Upper Cretaceous — Paleoalpine structure). This region is sharply demarcated from the northern part by dominant Tertiary structures, in the geological structure of the latter part Hercynian structures still dominate. The basement of the northern part of the collision zone (ca 300 km wide) is formed of Alpine (Saxonian) ruptured Paleozoids, mainly Hercynides (Ziegler 1984). The region is considerably peneplaned and is still being deformed. The chronological model of the neotectonic movement trends (Table 1) based on the analysis of small scale tectonics and measurements of the stress in situ shows that the neotectonic movement trends in last 5—10 Ma (the trends in the Alpides and in the part of the platform which is coupled with them are not the same) are in principle a continuation of post — Lower Sarmatian and in part post — Dacian movements (Procházková, Roth 1989).

The geological medium is considered to be a geodynamic open hierarchal system that develops by mutual causation of its inner and outer parts; the development of the system means that the future system state is a result of recent past system states. The origin of earthquakes are one of product of this system. The mathematical theory of the system analysis offers the method of the black box because we have not exactly defined the processes leading to earthquake origin. The process is sought, and therefore, an analysis of all available empirical data on earthquakes is essential, a fast treated in the following pages.

5. The data set used

In investigating earthquakes and deriving quantitative and qualitative characteristics in Czechoslovakia and the whole of Central Europe, we had to use all available sources of information and data. A complete list of more that one hundred references is contained in (Procházková 1984); the basic data sets were the publications by (Kárník 1968, Kárník, Michal, Molnár 1958, Kárník, Procházková, Bouček 1984, Procházková, Dudek 1982, Pagaczewski 1972, Kondorskaya, Shebalin 1982, Slejko 1982, Leydecker 1981, Carrozo et al. 1972, Ribarič 1982, Radu 1982, Sieberg 1940, Réthly 1952, Monus, Tóth, Zsíros 1983, Sponheuer 1952, Procházková, Kárník 1978, Kárník, Procházková, Schenková 1981, Drimmel 1980, ISC bulletins). The other publications applied were these that mainly appeared after 1984 (Procházková 1985, Procházková, Michek, Tobyáš 1989, Procházková 1989b, 1990a, 1991a, Zsíros, Monus, Tóth 1988) and archive materials of the geophysical establishments in Prague, Bratislava, Vienna, Moxa, etc. In the catalogues used, macroseismic data predominate over instrumental ones.

So far, earthquake catalogues have only given basic geometric and time data, and apart from that only the intensity in the epicenter or the magnitude. These quantities, however, do not carry information on the nature of the mechanical process that takes place in the earthquake focus, both prior to its origin, during the radiation of seismic energy and in the subsequent stage. Seismograms contain this kind of information, which is only partly covered due to the medium, through which the waves propagate from the focus to the recording site. On the basis of seismograms, therefore, we determine the stress field in the focus closely before the origin of a disturbance, and the direction of the fracture generated under the earthquake, or the direction of the fault, along which the slip occurred (earthquake mechanism), and the dynamic focal parameters. In the computation, we usually use simplified physical notions:

– We define an earthquake as a sudden brittle disturbance of a part of the massif due to mechanical forces (Červený 1983).
– In accordance, e.g. with Aki (1967), Aki, Paton (1978), Keylis-Borok (1959), Ritsema (1969), we characterize the earthquake mechanism by a couple of dipoles without the moment.

Only for a small amount of stronger shocks in the study area it was possible to compute earthquake mechanisms and to determine focal parameters of shocks (seismic moment, focal dimensions, stress drop, etc.). We cannot reckon with routine determinations of the mechanisms of weaker earthquakes until we have densified the network of Central European stations, actually, until we have built local arrays and constructed models of the structure of individual focal regions.

An assessment of the completeness of data on earthquakes by means of frequency graphs has shown that with greatest likelihood all earthquakes have been recorded in the entire study area; namely, all the earthquakes with epicentral intensities $I_0 \geqq 8°$ MSK-64 since about 13th century, $I_0 \geqq 7°$ MSK-64 since about 14th century, $I_0 \geqq 6°$ MSK-64since about the beginning of 16th century, $I_0 \geqq 5°$ MSK-64 roughly since the mid-nineteenth century, and $I_0 \geqq 4°$ MSK-64 in 20th century. Records of earthquakes with epicentral intensity $I_0 \geqq$ $\geqq 2-3°$ MSK-64 date from as late as 20th century. But complete data on these shocks have only been available since the sixties after a denser deployment of seismological stations which can localize even the shocks that people do not feel due to civilization noise. The data on weak seismic events are not transferred to international centres, and therefore, the shocks are not localized on a broader scale. The shocks are localized for special purposes only in particular regions and a particular time interval; they are not localized in the entire study area. Due to the inhomogeneity of data sets in the domain of weak events, some features, such as e.g. some properties of aftershock groups, cannot be systematically observed at all in the study area.

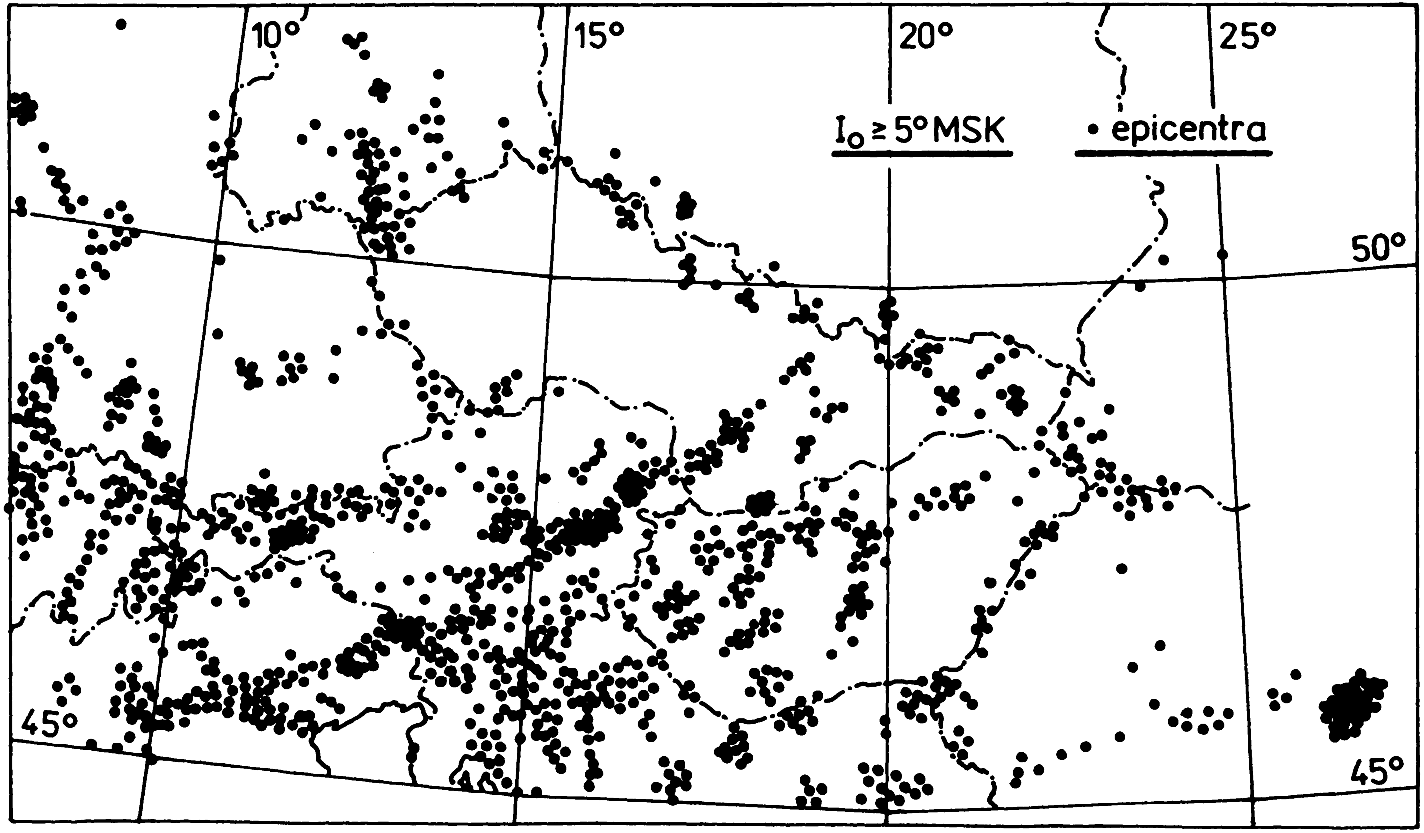

Fig. 4
Epicenter map.

6. Earthquake pattern

The specific feature of the region under study is low seismic activity on its greater part, which means that the study has to involve also analyses of historical earthquakes since instrumental data only include a short time interval, the last 50 – 80 years. The consideration of Vrancea, a very active region characterized by intermediate earthquakes, allows a comparison of the characteristics of a region with weak shallow seismicity with those of a region with high intermediate seismicity.

The map of epicentres of earthquakes with epicentral intensity $I_0 \geqq 5°$ MSK-64, Fig. 4, documents that the earthquake epicentres in the study area are unevenly distributed. The map contains data of the last five to eight centuries; the set of shocks in the map begins being regionally homogeneous since as late as the beginning of 19th century when cultural differences in Central Europe became balanced. Therefore, the distribution of epicenters of weaker shocks and of shocks from a longer time interval can be represented for partial regions only (e.g. Kárník, Procházková, Schenková 1981, Procházková 1976, 1984, Zsíros, Monus, Tóth 1988).

Maps of earthquake epicenters for individual areas, like Fig. 4 point to clustering of shocks into regions. In determining focal regions, our requirement is to combine individual clusters of foci into larger regions by incorporating in one region the clusters of foci that share the same characteristics of the seismic regime. In accordance with (Grin, Knauf 1978), we proceed from small clusters of foci connected with motions along one fault or system of parallel faults to bigger wholes. In the following text, focal regions are denoted by graphical names of areas, faults and towns. The maps that contain the faults, whose names are used in the present work, are presented in (Procházková 1984).

6.1 Description of focal regions

A contribution to the seismicity of every region is made by the foci that lie in the territory of the respective region, for one thing, and for the other, by the foci that lie outside the study region but are manifest by macroseismic effects in its territory. In the case of Czechoslovakia it concerns the earthquakes, whose foci lie in the foothill belt of the Alps in the Eastern, Western and Southern Alps, in the regions of the Franconian and the Swabian Jura, in Saxony, Poland, the Pannonian Massif, and even in the Vrancea region in Roumania. It has been eastablished that the strongest earthquakes:

- In central Germany (6. 3. 1872 Gera, 8° MSK-64) reach the area of West Bohemia by the isoseismal of 4° MSK-64.
- In the Swabian Jura (16. 11. 1911, $I_0 = 9.25°$ MSK-64, 3. 9. 1978, $I_0 = 8.5°$ MSK-64) reach the area of West Bohemia by the 4° isoseismal.

- In the Franconian Jura (10. 10. 1915, I_0 = 7° MSK-64) they reach the area of West Bohemia by isoseismals of 5° and 4°.
- In the Lechtal Alps (the Inn region, 13. 7. 1910, I_0 = 7.5° MSK-64) they reach the area of southwest Bohemia by the 4° isoseismal.
- In the region of Eastern Alps (Mur – Muerz – Leitha, 8. 10. 1927, I_0 = = 8° MSK-64) they reach the territory of Czechoslovakia by isoseismals of 5° and 4°.
- With epicenters in the Eastern Alps lying on the lines parallel to line Mur – Muerz – Leitha (15. 9. 1590, I_0 = 9° MSK-64) they reach the territory of Czechoslovakia by isoseismals of 6°, 5° and 4°.
- In Friuli (6. 5. 1976, I_0 = 10° MSK-64) they reach the area of Bohemia by the 4° isoseismal.
- In the Strzelin region (11. 6. 1895, I_0 = 7° MSK-64) they reach the areas of northeast Bohemia and Moravia by the 4° isoseismal only.
- In the Kraków region (3. 12. 1786, I_0 = 7.5° MSK-64) they reach the areas of Slovakia and Moravia by isoseismals of 7°, 6° and 5°.
- In Ruthenia (24. 10. 1965, I_0 = 7° MSK-64) they reach Eastern Slovakia by isoseismals of 5° and 4°.
- At the border of Hungary and Roumania (15. 10. 1834, I_0 = 8.5° MSK-64) they reach Eastern Slovakia by isoseismals of 6°, 5° and 4°.
- In the region of the Tisa river (8. 7. 1911, I_0 = 9.5° MSK-64) they reach the south of Slovakia by the 4° isoseismal.
- In the region of Monor, Jászberény (31. 1. 1925, I_0 = 8.5° MSK-64) they reach the south of Slovakia by isoseismals of 5° and 4°.
- In the region of Mór, Budapest (14. 1. 1810, I_0 = 8.5° MSK-64, 19. 2. 1951, I_0 = 7° MSK-64) they reach south of Slovakia by isoseismals of 6°, 5°, etc.
- In the region of the Raaba river (14. 5. 1942, I_0 = 6° MSK-64) they reach the south of Slovakia by the 4° isoseismal only.

The sum of the contribution by the two mentioned earthquake groups is shown in the map of maximum observed intensities. The last version of a map of this type for the territory of Czechoslovakia is contained in the publication (Kárník et al. 1988); this version is supposed as a part of revise building code of the ČSFR. The maps for single countries of Central Europe, including general maps for Central and East Europe are presented in (Kárník, Procházková, Schenková 1981). These maps furnish general information for regional planning. It has to be noted that, as a rule, they only generalize the existing information on earthquakes and their observed effects, i.e. they presume invariability of the earthquake activity in focal regions in time. They do not define the regions that did not manifest themselves by earthquakes in the historical period.

Owing to the fact that for physical reasons (each rock massif in the lithosphere undergoes continuous development), we cannot presume invariability of the process of earthquake occurrence in time and space, we study the process in individual focal region separately. Based on the analysis of data sets, the following characteristics (I_0 – epicentral intensity, h – focal depth) apply to individual regions:

Central part of the Bohemian Massif

In the region records of 34 earthquakes are available from the period 1036 to 1988, $I_0 \leqq 5°$ MSK-64. The earthquake of 8. 4. 1898 in the area of Mělník was attended by distinct acoustic effects. The majority of shocks are in the area of Kutná Hora, where at least some shocks are likely to be connected with mining activity. Other shocks occur in the areas of Kladno and Příbram and their connection with mining activity is also obvious. The foci of shocks also occur in the area of the Litoměřice deep fault, or on its continuation – the Stráž fault (e.g. shocks in Rovensko pod Troskami on 30. 3. 1928, in Bělá pod Bezdězem on 7. 2. 1949), and in the area of the Jáchymov deep fault (e.g. shocks in Rožmitál pod Třemšínem on 20. 8. 1978, in Plasy on 17. 4. 1521, in Blovice on 23. 4. 1881 and 16. 9. 1977), and on the SW segment of the Kladno fault running across Plzeň (e.g. on 21. 1. 1909, 20. 9. 1973, 21. 9. 1978).

Czech-Moravian Highlands

Distinct acoustic effects are described with earthquakes. Since 1329 we have had records on 18 shocks, mostly from the area of Jihlava, where we suppose a connection of shocks with mining activity. Shocks also occur in the areas of Křemešník (22. 10. 1887) and of Želiv (1927), where they are likely to be connected with the Sázava deep fault and some local shocks with the Přibyslav deep fault. Earthquakes in the highlands apparently do not exceed 5° MSK-64, their macroseismic fields covering several villages at the most. A significant event are earthquake swarms near Jindřichův Hradec, Rajchéřov (1932), Stráž n. Než. (1860), Kunějov (1924–25) and Ličov (1854–59), which are distinguished by acoustic effects (detonations), some swarms last as many as two years.

South Bohemia

Since 1590 we have had records on 27 local earthquakes; $I_0 \leqq 5°$ MSK-64. The shocks are connected with:

- the Blanice furrow (Třeboň 8. 12. 1877);
- the Jáchymov deep fault (Nové Hrady 6. 2. 1796, 17. 7. 1875);
- the Kaplice fault (line České Budějovice, Český Krumlov, Vyšší Brod);
- the Lhenice trough (Chvalšiny, Bavorov 1. 2. 1880, 27. 5. 1882, 20. 10. 1909, 11. 2. 1900, 29. 4. 1983);
- the Šumava fault (Lenora, Horní Vltavice, Boubín – e.g. 28. 5. 1929, 20. 8. 1978).

Austrian part of the Bohemian Massif

Shocks occur in the Linz area (1. 10. 1785, 26. 10. 1865, 17. 6. 1972) and in the line along the Krems river (6. 6. 1982, 22. 11. 1862, 5. 1. 1865, 10. 3. 1971); $I_0 \leqq 6.5°$ MSK-64. The foci are connected with the Kaplice — Rodel fault intersecting the Alpine foredeep which in these places strikes W—E.

SW Bohemia and the adjoing region

In the area of the Bavarian and Bohemian Forests, 71 local shocks have been recorded since 1197; $I_0 \leqq 6.5°$ MSK-64. Shocks occur in the area of:

- Domažlice and Horšovský Týn (Bohemian quartz dike — e.g. 18. 10. 1688, 24. 4. 1858);
- Grafenau and Thalberg (Bavarian quartz dike — e.g. 5. 1. 1897);
- Přimda, Stráž u Tachova, Vítkov and Studánka (Tachov fault — e.g. 24. 11. 1902, increased seismic activity in the years 1902—14).

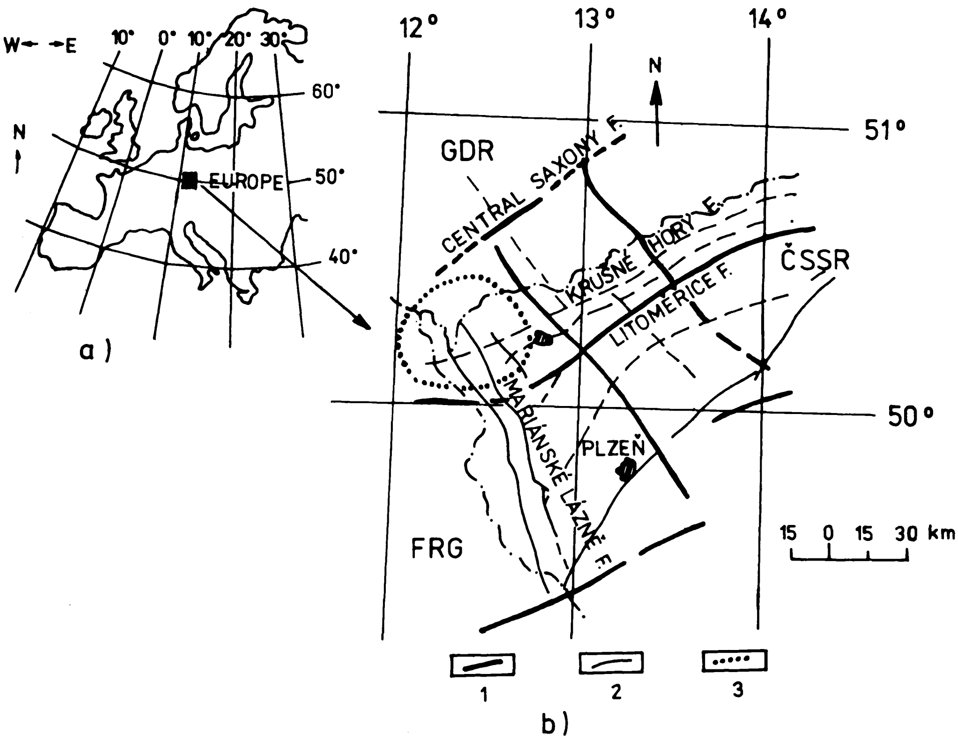

Fig. 5

Focal earthquake swarm region. Scheme of important fault structures of the Western Bohemia and surroundings:

1 — deep faults,
2 — important faults of first order,
3 — focal regions of earthquake swarms.

Further, weak shocks are in the vicinity of:
- Nýrsko (e.g. 9. 10. 1915);
- Titlingen (Donau fault);
- Stříbro (1. 10. 1822);
- Planá – Chodová Planá (e.g. 6. 2. 1788, 22. 7. 1915).

Aš – Skalná – Kraslice – Bad Elster – Selb

Shocks have been recorded since 1198; $I_0 \leqq 7°$ MSK-64. Earthquake swarms were recorded in the years 1198, 1522, 1674, 1701, 1771, 1824, 1850, 1897, 1901, 1903, 1908, 1911, 1929, 1936–37, 1962, 1985–86. The data are mostly macroseismical; instrumental data on weaker shocks are available for the years 1909–65 when the seismic station in Cheb was operating. Since 1909, data on stronger shocks have been available from seismic station Hof (sensitive short-period seismographs were installed in this station as late as in 1972), and systematically since 1968 when the array on the territory of the GDR was put into operation.

TABLE 2.

Properties of earthquake swarms in the Aš – Skalná – Kraslice – Bad Elster – Selb region.

f_2 from $\log N_c = e_2 - f_2 I_0$,

r_k – correlation coefficient of the dependence of $\log N_c(I_0)$,
n_a – the number of partial active periods of the swarm,
τ_a – time duration of partial active periods,
Int. f_2 – the interval that contains values f_2 determined for the swarm partial active periods,
τ_s – approximate time duration of the swarm,
h – focal depth,
n – symbol of event.

n	Swarm year	f_2	r_k	Max I_0 ° MSK-64	n_a	τ_a days	Inter. f_2	τ_s weeks
1	1824	0.50	−0.985	6.5	2	–	–	4
2	1897	0.68	−0.984	6.5	4	4–6	0.58–0.64	5
3	1900	1.00	−0.988	5.5	2	3–5	0.88–1.02	8
4	1901	0.55	−0.949	5	–	–	–	7
5	1903	0.65	−0.974	7	4	4–6	0.54–1.06	12
6		–	–	–	–	–	–	–
7	1908	0.58	−0.971	6.5	3	4–7	0.55–0.66	6
8		–	–	–	–	–	–	–
9	1929	0.63	−0.991	5.5	–	–	–	1
10	1936–37	1.08	−0.969	5	2	4–6	–	7
11	1962	0.95	−0.943	5.5	–	–	–	8
12	1973	1.11	−0.997	5	2	–	–	4
13	1983	–	–	–	–	–	–	–
14	1985–86	0.56	−0.963	7	4	4–6	0.35–0.63	8

Notes to events in Table 2.

2 – The focal depth of shocks with $I_0 \geqq 6°$ MSK-64 grew; foci of stronger shocks connected with the Krušné hory Mts and the Mariánské Lázně fault systems.

3 – The focal depth of shocks with $I_0 \geqq 5°$ MSK-64 decreased; foci of stronger shocks connected with the Krušné hory Mts. fault system.

4 – Foci of the strongest shocks connected with the Mariánské Lázně fault system.

5 – Partial active period II: shocks with $I_0 \geqq 6°$ MSK-64 had $h = 5-9$ km; partial active period III: shocks with $I_0 \geqq 6°$ MSK-64 had $h = 3$ km; foci of the strongest shocks connected with the Krušné hory Mts fault system.

6 – Minor shock groups of swarm nature that lasted several days occurred in the years 1904, 1905, 1906, February 1908.

7 – Focal depth of shocks with $I_0 \geqq 5.5°$ MSK-64 grew during the first two partial active periods; according to the character of Benioff graphs, partial active period III can be characterized as a quietening of the activity; foci of strong shocks connected with the Krušné hory Mts and Mariánské Lázně fault systems; two displacements of strongest shocks foci SW–NE.

8 – Minor shock groups of swarm nature occurred in the years 1909, 1911, 1912, 1914, 1915 (values $f_2 \sim 0.70$);

9 – Focal depth of shocks with $I_0 \geqq 5°$ MSK-64 grew; foci of strongest shock connected with the Krušné hory Mts fault system.

10 – Focal depth of shocks with $I_0 \geqq 5°$ MSK-64 decreased.

11 – No macroseismic data were assembled.

12 – Focus of the strongest shock connected with the Krušné hory Mts fault system.

13 – A shock group of swarm nature (approx. 130 shocks with Iida magnitude $M_I \leqq 1.2$) in the year 1983.

14 – Over a broader time interval (about ± half a year) around the main part of the swarm, weak shocks or small groups of weak shocks occurred. Focal depth $h = 3-12$ km, most frequently between $5-8$ km. Single shocks were noticed through acoustic effects by local citizens as early as the beginning of 1985. Early in December 1985, the thundering acoustic character was assuming increasing intensity. Weaker shocks were only accompanied by a rumbling sound. Stronger shocks were manifest by a swinging movement of objects and the strongest by material damage. The strongest shock: Dec. 21, 1985, at 10h16m UTC, U.S. Geol. Survey 50.333° N, 12.325° E, $M_L = 5.1$ (GRF); $I_0 = 7°$ MSK-64, $h = 11$ km. It caused a great amount of material damages, e.g. collapsed chimneys, damage of chimney masonry, cracks in facades, fall of fairly large pieces of plaster, etc., in the epicentral area. From the analysis of microbarograph records, it follows that the strong acoustic effects, often reported by people in the focal region, that coincide with the sound propagation through the air, were not recorded by the barometric instruments. The acoustic pressure would have to be generated by a high frequency body wave as well as surface waves at the point of observation. There were also observed: disrupted the groundwater regime, some light effects, rise of a strong wind before stronger shocks, health problems of some observers. The instrumental data document the changes of the foci possition and/or changes of the fault orientation and slip direction of the earthquake source.

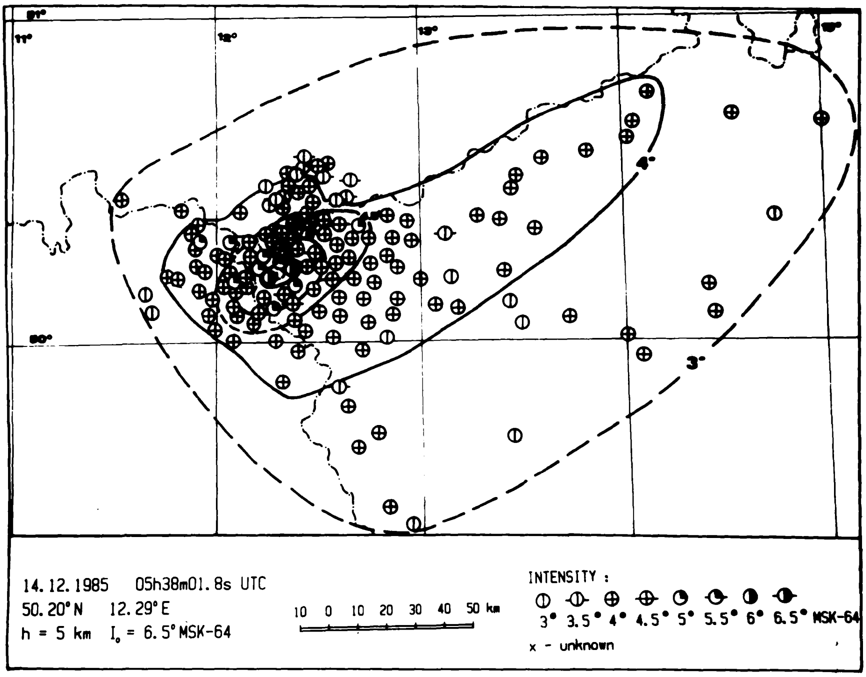

Fig. 6a
Isoseismal map.

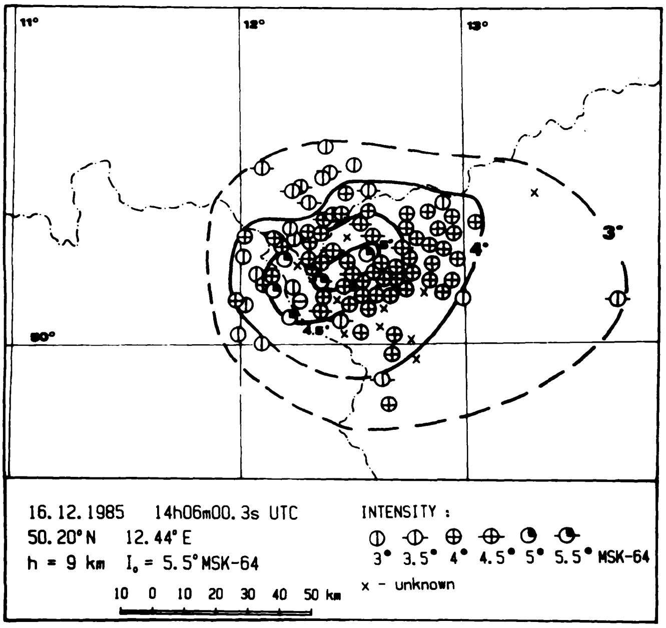

Fig. 6b
Isoseismal map.

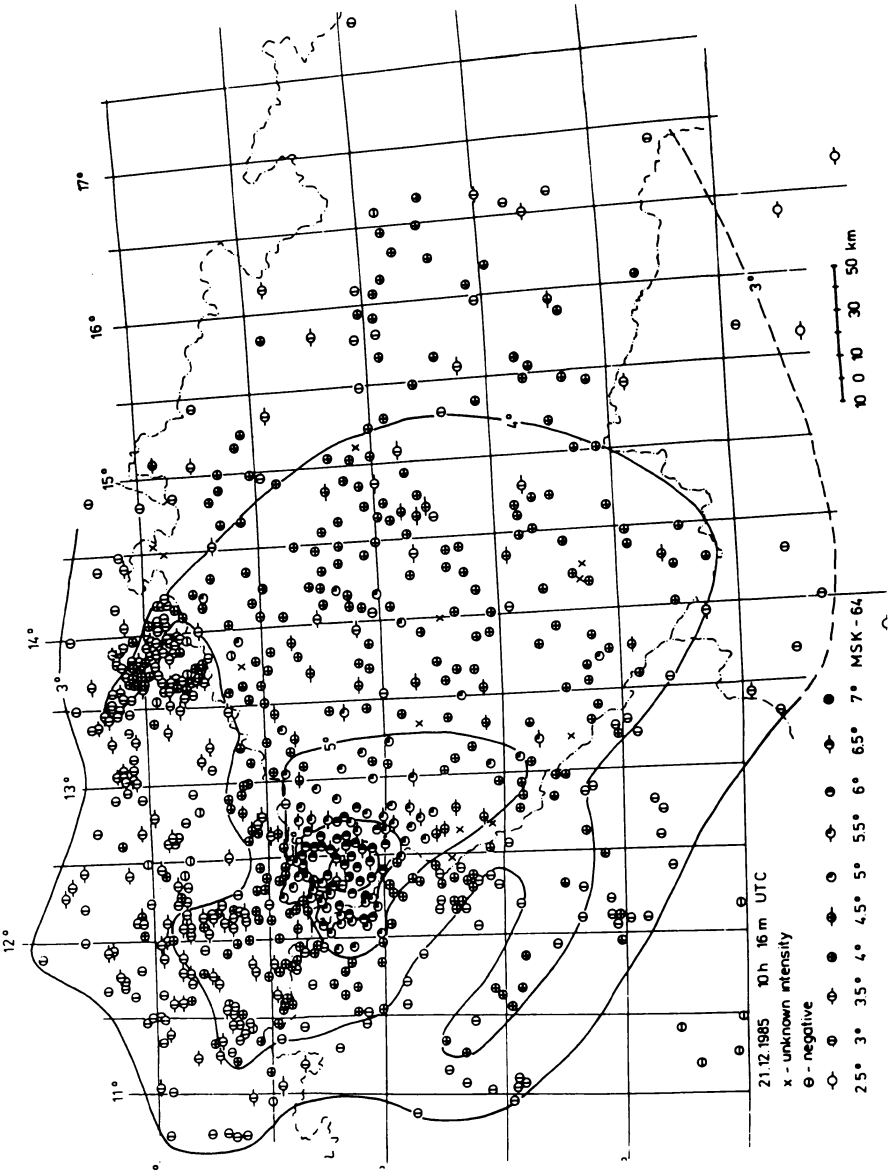

Fig. 6c
Isoseismal map.

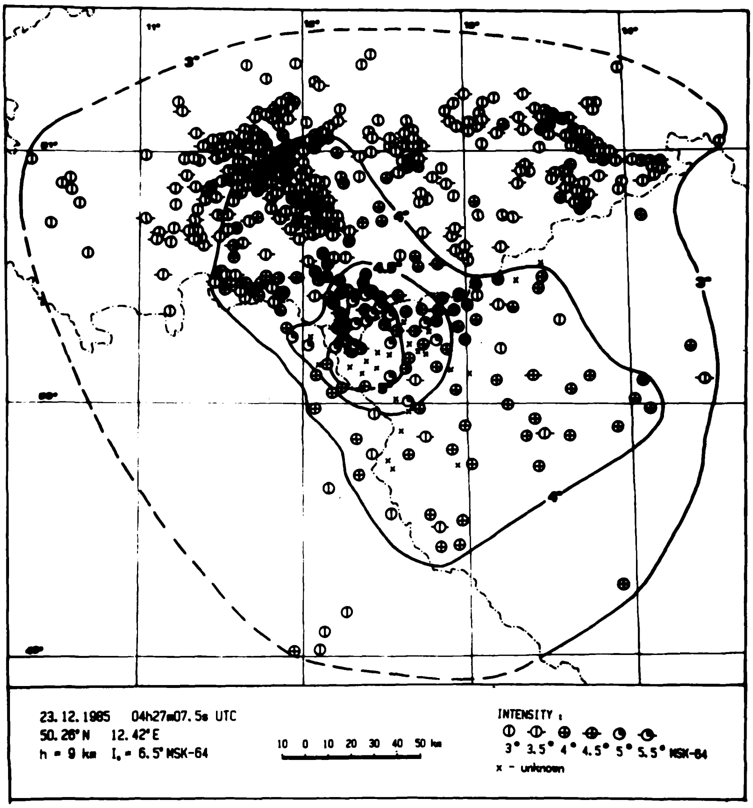

Fig. 6d

Isoseismal map.

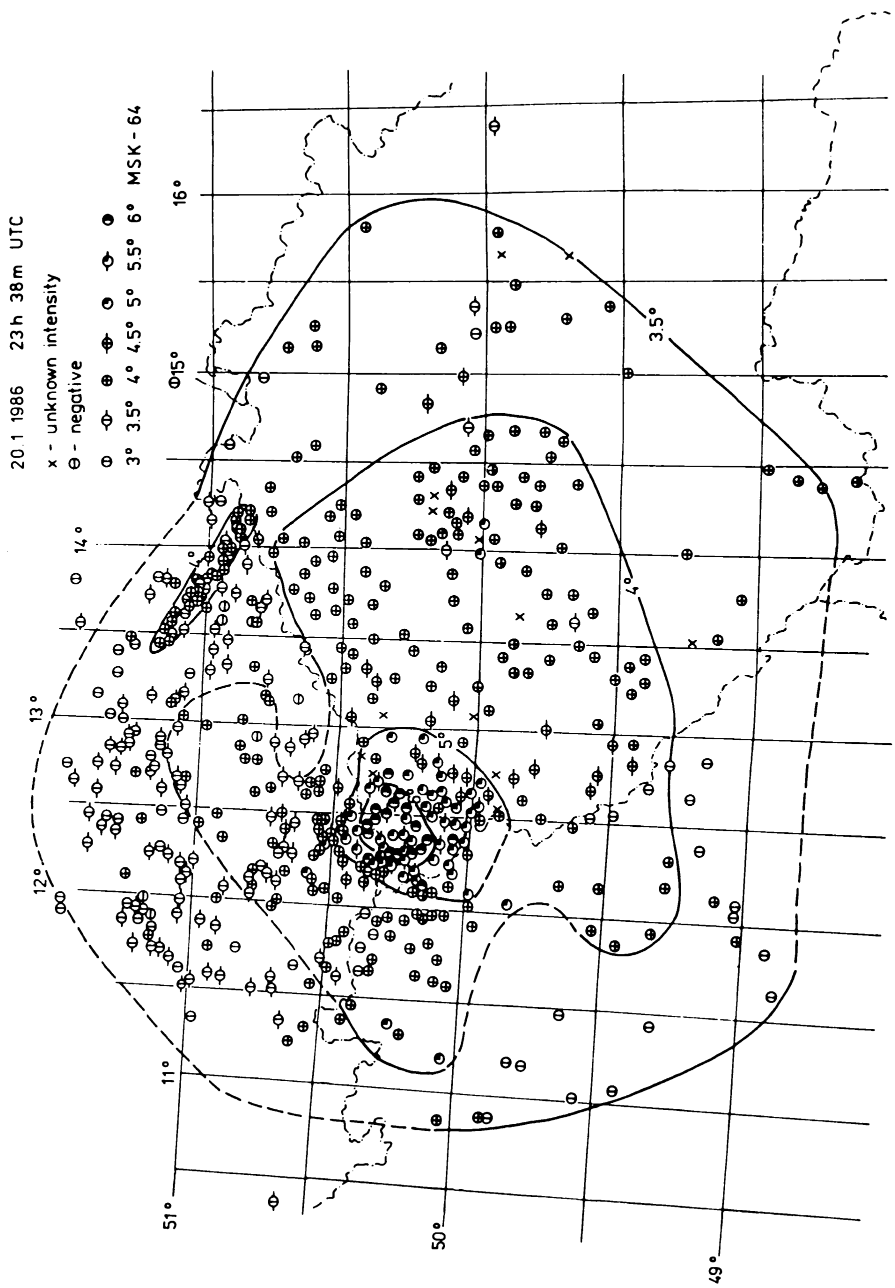

Fig. 6e
Isoseismal map.

The focal region of swarms (50.2°—50.4° N, 12.2°—12.6° E) lies among the faults: the Jáchymov deep fault, the Litoměřice deep fault and the Central Saxonian fault (Fig. 5). Shocks are connected with the Krušné hory Mts fault, or are situated on a line parallel to it which lies NW of it or are connected with the Mariánské Lázně fault and with the continuation of the Tachov fault. Weak earthquake swarms afflict only a part of the delineated area, under strong swarm shocks foci occur throughout the area. The shocks of earthquake swarms are accompanied by underground rumbling, the yield of the Karlovy Vary springs is increased, sometimes the water of the springs gets turbid. The duration time of swarms is directly proportional to the magnitude of the strongest shocks in the swarm; it varies from a couple of days to a couple of weeks (in the last two centuries, earthquake swarms lasted two months according to macroseismic observations). Individual swarms consist of two or more active periods, between which the activity is low. Active periods are concentrated round the strongest shocks of a swarm, sometimes as many as hundreds of shocks occurring every day and lasting 3—6 days.

The last earthquake swarm afflicted Western Bohemia at the turn of the years 1985 and 1986. Properties of swarms are in Table 2 (Procházková ed. 1987b, 1988a). Figure 6 shows the isoseismal maps of five shocks, we can see that they are not the same — different size, focal depth and focal mechanism. Figure 7 shows

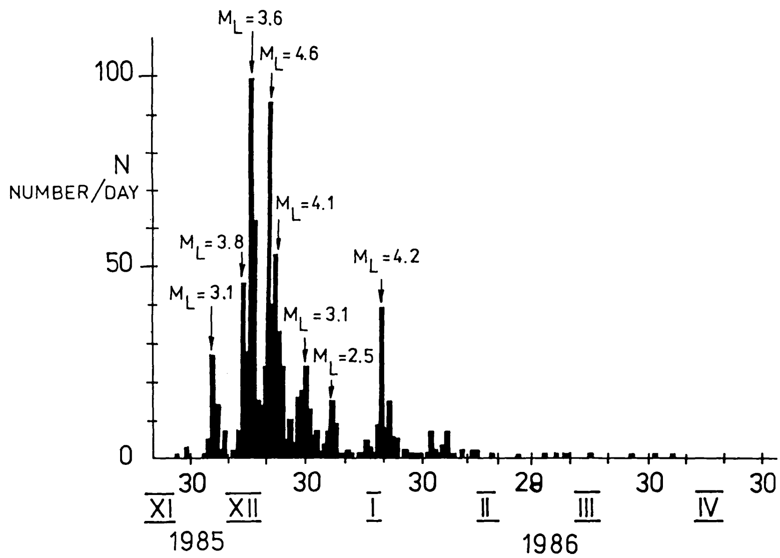

Fig. 7

Dependence of the daily number of shocks *N* recorded macroseismically on time during the 1985—86 (November 1985—April 1986); local magnitudes of the strongest events in individual active periods are marked.

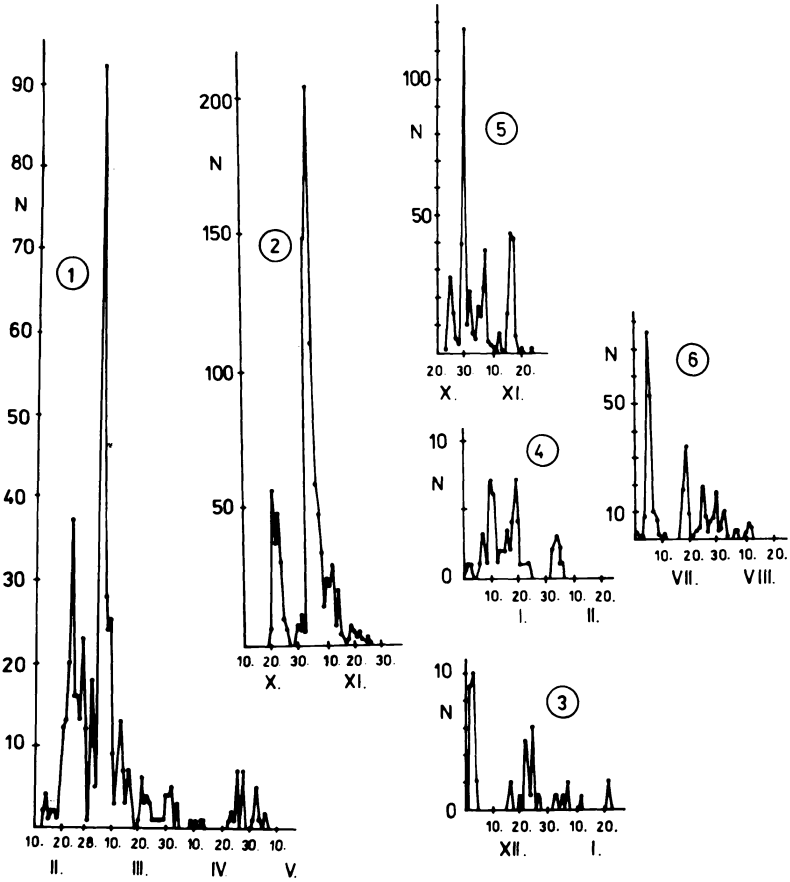

Fig. 8a

The daily number of shocks N as a function of time t for the earthquake swarms, the circled numbers mark the earthquake swarms:

1: Feb. – May 1903;
2: Oct. – Nov. 1908;
3: Dec. 1936 – Jan. 1937;
4: Jan. – Feb. 1824;
5: Oct. – Nov. 1897;
6: Jul. – Auf. 1900.

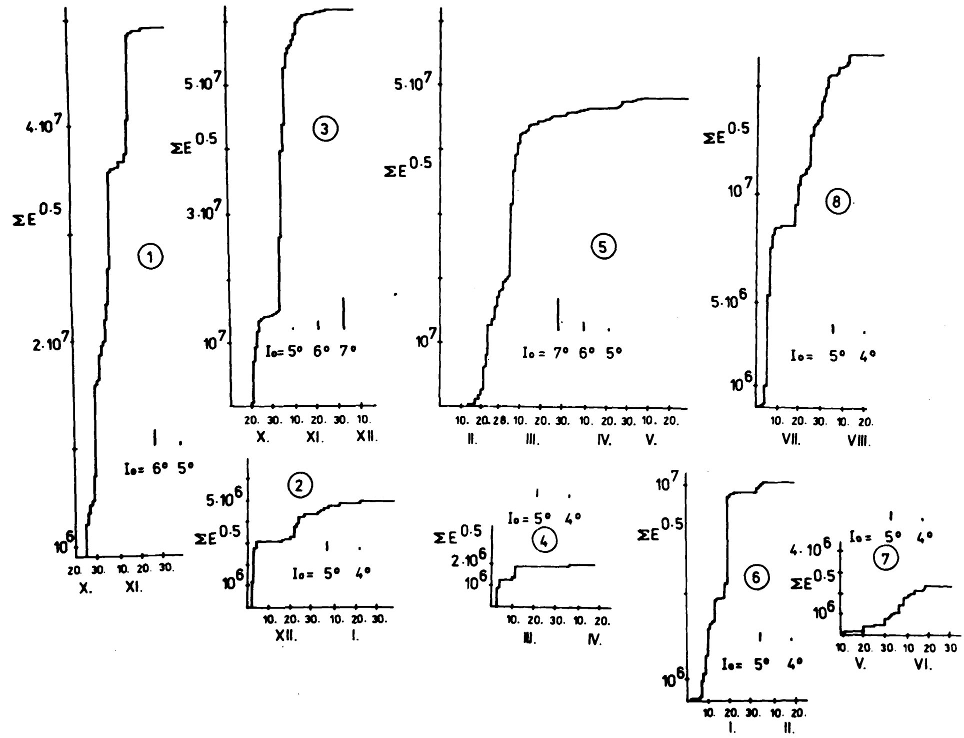

Fig. 8b

Benioff graphs for the earthquake swarms in Western Bohemia-Vogtland region; the circled numbers mark the earthquake swarms:

1: Oct. – Nov. 1897;
2: Dec. 1936 – Jan. 1937;
3: Oct. – Nov. 1908;
4: Mar. – Apr. 1973;
5: Feb. – May 1903;
6: Jan. – Feb. 1824;
7: May – Jun. 1901;
8: Jul – Aug. 1900.

The earthquakes have not been aggregated in the graphs; one value for each day has been plotted, corresponding to the daily sum of $E_i^{0.5}$, $E_i[J]$ being the seismic energy released during the i-th shock.

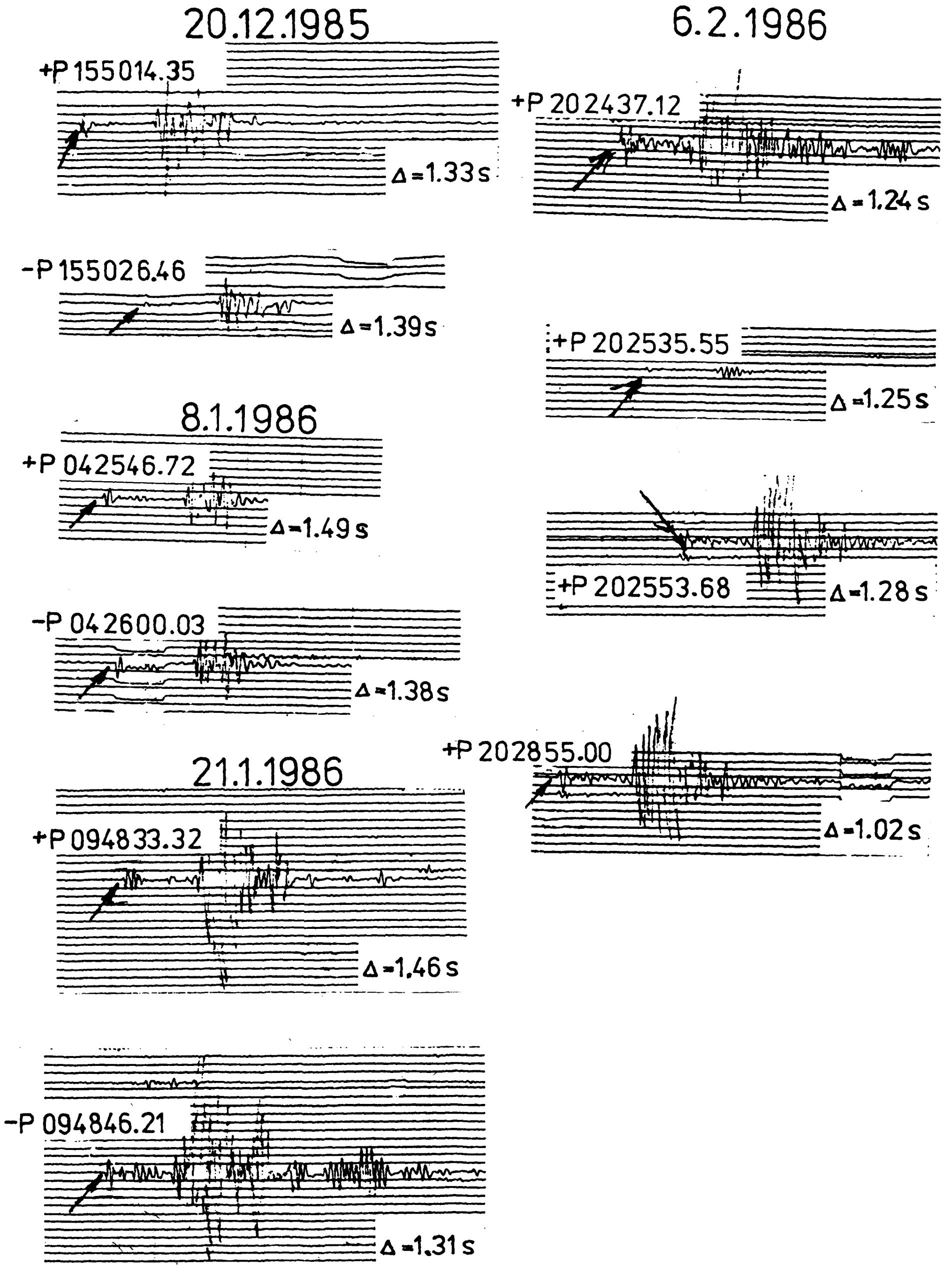

Fig. 9

Seismograms of selected shocks of the 1985–86 earthquake swarm in Western Bohemia recorded in Oloví (in one minute there are shocks with the different directions of the first onset of the P waves).

relationships between the daily number of shocks N and time t; we can observe a coincidence with the past earthquake swarms, Fig. 8. The analysis of seismograms of the last swarm, especially of the local seismological stations, examples in Fig. 9, showed that single shocks differ in size, focal position and focal mechanisms. A space-and-time study of these swarm shock characteristics reveals great rapid changes of the local tectonic stress during the swarm and a very complex faulting process during the swarm.

Komořany area

Since 1505, 80 shocks have been recorded; $I_0 \leqq 6.5°$ MSK-64. A small swarm occurred in the year 1896 (31 shocks with $I_0 \leqq 5.5°$ MSK-64 recorded macroseismically); it lasted 6 days. The focal region is situated on the intersection of the Krušné hory Mts fault and the near perpendicular fault (Procházková et al. 1986).

Saxony and Thueringer Wald

Earthquakes are connected with the Central Saxonian deep fault and with a deep fault of the NW—SE direction. The maximum observed earthquake, $I_0 \leqq 8°$ MSK-64, occurred in the vicinity of Gera on 1872.

Bavaria and Swabia

Earthquakes, $I_0 \leqq 7°$ MSK-64, are connected with the Donau fault and those, $I_0 \leqq 9.5°$ MSK-64, in the Swabian Jura are connected with the continuation of the Lago di Como deep fault — upper part of the Rhine River. Stronger shocks are felt in the Bohemian Massif, e.g. Fig. 10. Macroseismic effects intensify also in the Thueringen Basin, which exhibits pronounced subsidence tendencies at present. The increased seismic activity in the Swabian Jura has been observed as late as in this century.

Northeast Bohemia and ambient area

The foci of shocks in Northeast Bohemia and the ambient area usually lie in the areas of Rtyně v Podkrkonoší in the Krkonoše Piedmont and of Úpice (Hronov—Poříčí fault, $I_0 \leqq 7.5°$ MSK-64). In the case of these shocks, a systematic local increase of intensities is observed in the areas of Jablonec and Tanvald. Under earthquakes distinct acoustic effects and disturbances in the underground water regime are observed.

The last macroseismically felt earthquake occurred here on May 7, 1984 at 03h19m20s UTC (Procházková 1987); Fig. 11 shows the isoseismal map and Fig. 12 shows the seismograms recorded at the seismographic stations of Kašperské Hory and Průhonice. One foreshock and one aftershock were observed.

Further, the shocks are in the area of:

- the towns of Goerlitz and Klodzko (Intra—Sudetic fault, $I_0 \leqq 6°$ MSK-64, e.g. 10. 2. 1562);

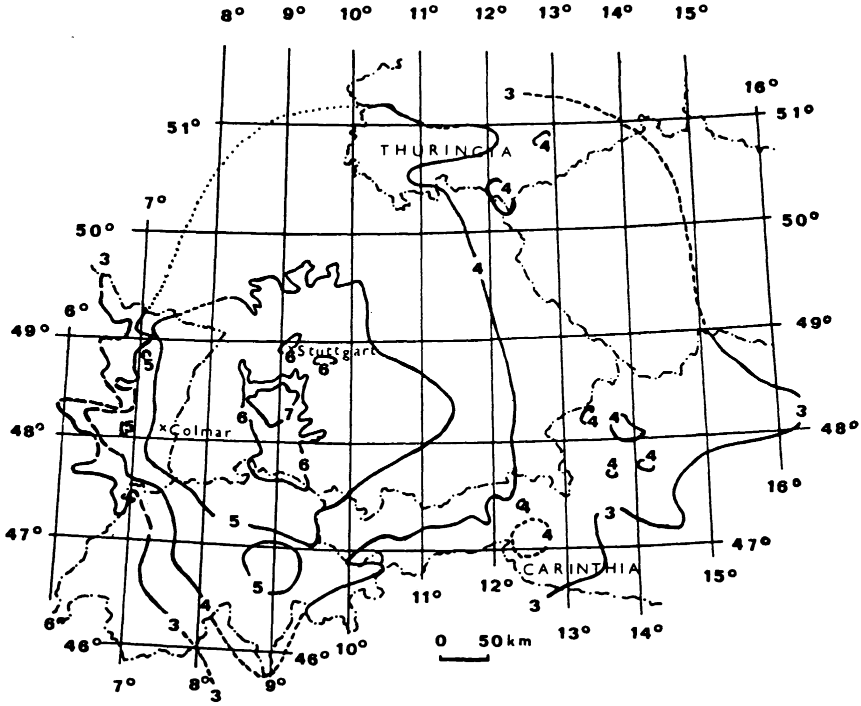

Fig. 10
Isoseismal map of earthquake of September 3, 1978 in the Swabian Jura.

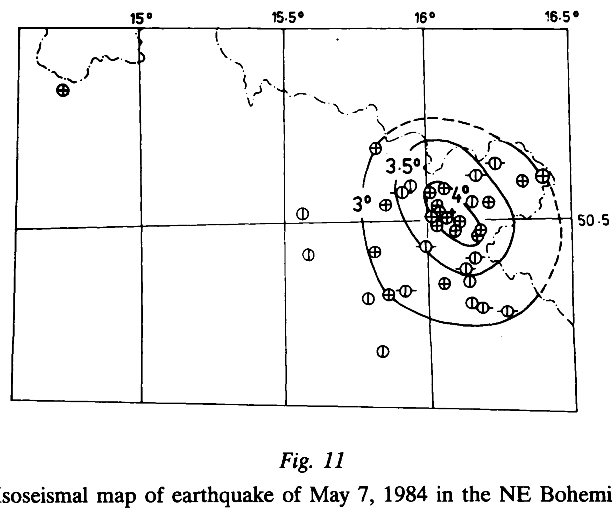

Fig. 11
Isoseismal map of earthquake of May 7, 1984 in the NE Bohemia.

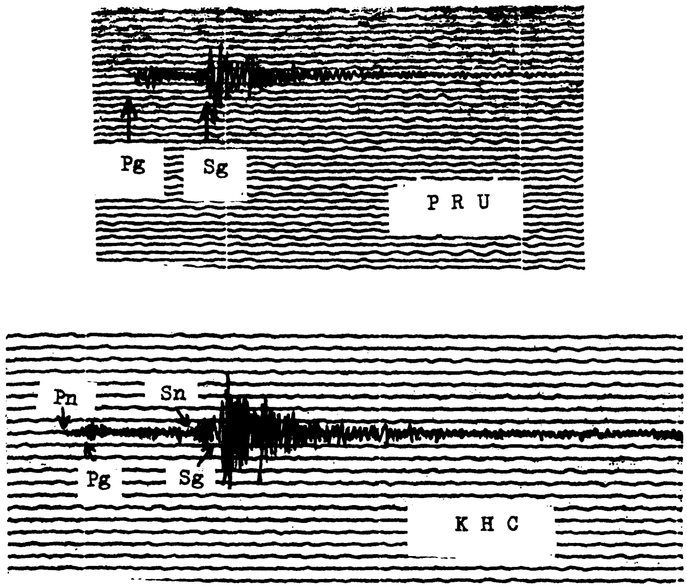

Fig. 12

Seismograms of earthquake of May 7, 1984 in the NE Bohemia recorded at Průhonice (PRU) and Kašperské Hory (KHC).

- Lusatia fault (e.g. 30. 4. 1908, 4. 7. 1980, $I_0 \leqq 4°$ MSK-64);
- Stráž fault (e.g. a shock on 5. 10. 1877 in Polubný, $I_0 \leqq 4°$ MSK-64);
- Frýdlant (e.g. 14. 1. 1804, 7. 3. 1915, 30. 6. 1979);
- the Jílovice fault (Nová Paka, Hradec Králové, Vysoké Mýto, $I_0 \leqq 5°$ MSK-64, e.g. 6. 12. 1606, 29. 12. 1620, 10. 10. 1980, 10. 8. 1987);
- Kraslice graben (e.g. shocks in the vicinity of Žamberk 14. 6. 1945, 28. 6. 1982, $I_0 \leqq 5°$ MSK-64);
- the fault parallel to the Oder Lineament (e.g. 11. 6. 1895 in the vicinity of Strzelin, $I_0 \leqq 7°$ MSK-64).

Moravia and the ambient area of Poland

Since the year 1014, a total of 139 shocks have been recorded in the areas of Moravia and the adjoining part of Poland. Except for the shocks on 22. 8. 1785 and 27. 2. 1786 in the area of Těšín, whose focal depths were 10 and 30 km, respectively, the others were most likely shallow. The foci in the area of Těšín lie in a region, where the Carpathians overlie the Bohemian Massif, whose depth here is small, about 2.5 km (borehole Krásná 1 below Mt. Lysá). From the data on the depths of shocks it ensues that the foci of both shocks are in the Bohemian Massif, and that they are probably connected with the subduction of the Bohemian Massif under the Carpathians.

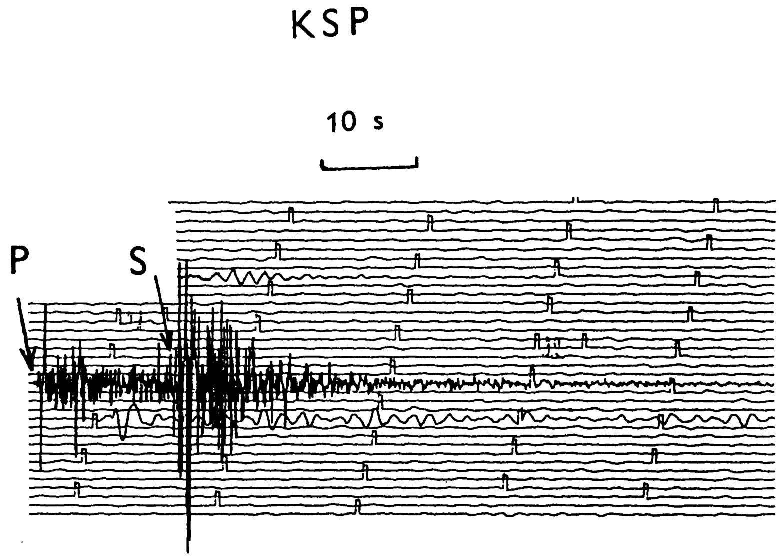

Fig. 13

Seismogram of earthquake in the area of Šumperk and Kouty n. Des. on Sept. 10, 1986 at 23h17m47.18s UTC recorded by the seismographic station Ksiaz (KSP).

The foci of shocks are connected with:

- the deep fault of the Červenohorské Saddle (the area of Šumperk and Kouty n. Des., $I_0 \leqq 5.5°$ MSK-64, e.g. 4. 5. 1616, 26. 11. 1878, 24. 7. 1935, 10. 9. 1989 – the seismogram of this last strong earthquake, $I_0 = 5.5°$ MSK-64, recorded by the seismographic station Ksiaz (KSP) is in Fig. 13);
- the Bušín fault (the vicinity of Litovel, Olomouc, Přerov, $I_0 \leqq 4°$ MSK-64, e.g. 1495, 2. 7. 1635, 30. 11. 1981);
- Boskovice graben and Bíteš fault ($I_0 \leqq 4°$ MSK-64, the region of Jaroměřice, Brno, Znojmo, e.g. 15. 4. 1748, 21. 3. 1977, 11. 6. 1982; the region of Dalešice and Krhov, e.g. 10. 10. 1927, 5. 2. 1949);
- Kynšperk fault (e.g. Svitavy 31. 3. 1908, $I_0 \leqq 3.5°$ MSK-64);

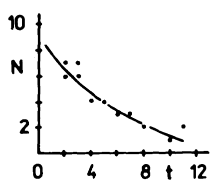

Fig. 14

Dependence of the number of aftershocks N on time t [days] calculated from the main shock on 12. 4. 1931.

– Dyje fault (the vicinity of Brumovice 2. 12. 1874, 18. 1. 1886, $I_0 \leqq \leqq 3.5°$ MSK-64);
– Šternberk – Horní Benešov fault (vicinity of Zlaté Hory and Hlubčice, $I_0 \leqq 5.5°$ MSK-64, e.g. 13. 2. 1786);
– fault Zlatov – Krnov ($I_0 \leqq 6.5°$ MSK-64, in the region of Opava, e.g. 1591, 14. 1. 1827, swarm in 1931, 3. 9. 1934; Fig. 14 shows $N(t)$ under aftershocks for 1931 and Fig. 15 shows the Benioff graph for the whole sequence);
– Oder lineament ($I_0 \leqq 4°$ MSK-64, shocks in the area of Wroclav and Legnice e.g. 24. 1. 1775, probably lie on the intersection of the Oder lineament with the Přibyslav deep fault);
– the boundary fault of the Oder Hills ($I_0 \leqq 7.5°$ MSK-64, $h \leqq 30$ km, area of Nový Jičín, Ostrava, Bohumín, e.g. 18. 11. 1014, 1. 5. 1715, 22. 8. 1785, 27. 2. 1786, 15. 1. 1855, 9. 1. 1936, 23. 3. 1977).

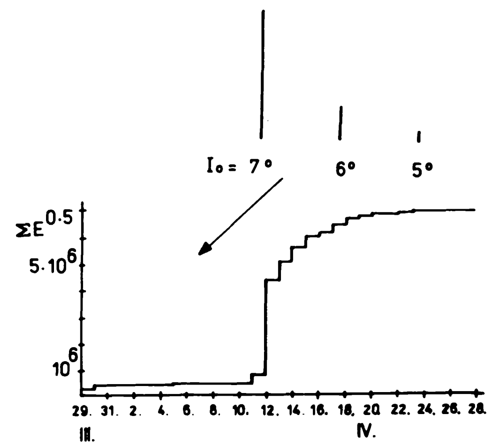

Fig. 15

Benioff graph for earthquakes in region Opava between 29. 3. – 28. 4. 1931; $E_i[J]$ is energy, t [days] is time.

Little Carpathians

Since 1515, 236 shocks have been recorded, $I_0 \leqq 8.5°$ MSK-64. The foci of these shocks are connected with the Záhorie – Humenné deep fault, which forms a deep-seated interface between the Bohemian Massif and the block of Slovakia. In the area of Dobrá Voda, foci lie on the intersection of the fault mentioned and the Dobrá Voda fault, which belongs to the fault system running from the Nesvačily trough as far as Jablonica on the NE margin of the Little Carpathians. The area of Stupava – Pernek – Modra, also characterized by strong shocks, probably lies on the intersection of the faults as well, namely of the Záhorie – Humenné deep fault, parallel to the Dobrá Voda fault, and the Danube fault. The analysis of the data

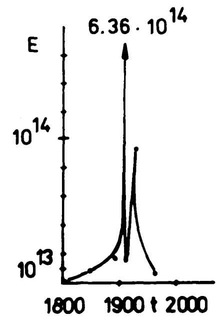

Fig. 16

Total annual energy $E[J]$ released under earthquakes in the Little Carpathians in the years 1800–1988.

obtained after the year 1700 shows that in this area, an earthquake with epicentral intensity $I_0 \geqq 6°$ MSK-64 occurs every 50 years. The active period since the year 1800 contains two maxima of earthquake activity, namely, in the years 1906 and 1930, Fig. 16.

A shock with $I_0 \geqq 7°$ MSK-64 in the area of Pernek was always followed by a strong shock in the area of Dobrá Voda. Following shocks with $I_0 \geqq 8°$ MSK-64, increased activity lasts several years.

Northern Slovakia and ambient area

Earthquakes are probably connected mainly with the Zahorie–Humenné deep fault. They are in the region of Trenčín and Žilina ($I_0 \leqq 7.5°$ MSK-64); since 1600 53 shocks, e.g. 21. 9. 1600, 1613, 15. 1. 1858. In the area of Trenčín and Trenčianské Teplice the foci are probably on the intersection of the Záhorie–Humenné and Štiavnica–Přerov deep faults.

The foci are also in the area of Kraków ($I_0 \leqq 7.5°$ MSK-64); since 1016, 7 shocks have been recorded, e.g. 31. 1. 1259, 3. 12. 1786, 8. 3. 1942. The foci in the Kraków region occur in the region of the contact of the East – European Platform, the Hercynides and of the Alpine – Carpathian orogen. The strongest shock on Dec. 3, 1786 followed strong shocks in the Těšín area (after 9 months).

The shocks are in the area of:

- Zakopané and Kežmarok ($I_0 \leqq 7°$ MSK-64, since 1453, 29 shocks have been recorded, e.g. 5. 6. 1643, 28. 5. 1966);
- High Tatra Mts (e.g. 9. 8. 1662, 7. 2. 1839);
- Partizánské, Prievidza, Martin and Dolný Kubín (since 1798, 6 shocks have been recorded).

Central Slovakia

The shocks are in the Ľubietová area ($I_0 \leqq 6.5°$ MSK-64, e.g. 11. 7. 1830 and in the region of the Vepor deep fault. The foci of strong shocks (1441 – I_0 =

= 9° MSK-64, 1443 – I_0 = 8° MSK-64) are likely to have lain on the intersection of the Vepor and Štiavnica – Přerov deep faults. Brouček's isoseismal map (Procházková, Kárník, eds 1978) and macroseismically determined focal depth h = 20 km practically rule out a connection of the 1443 shock with mining activity. In Central Slovakia, 41 shocks have been recorded since 1441. Some of them in the area of Banská Štiavnica and Kremnica may have been connected with mining activity.

Komárno region

The area of Komárno is situated in the SE margin of a region characterized by rapid subsidence in the Neogene and the Quaternary. It is a region of a probable intersection of the Danube, Vepora deep faults and the Komárno – Pezinok fault. Since 1599, records of 824 shocks are available. For the strongest shock of 28. 6. 1763 (I_0 = 9.5° MSK-64) there exists only a schematic isoseismal map. Conspicuous elongation of isoseismals in the more distant part into the Bohemian Massif and the Pannonian lowlands, and the focal depth suggest the same properties of the deep underlying rock throughout the area. The duration time aftershocks τ_s ~ 3 months up to 2.5 years is directly proportional to the shock size:

$$\tau_s[\text{year}] = (0.24 \pm 0.84) + (0.49 \pm 0.11)\, I_0 ,$$

it is valid for $I_0 \geqq 5°$ MSK-64. We have documented here only one active period, Fig. 17.

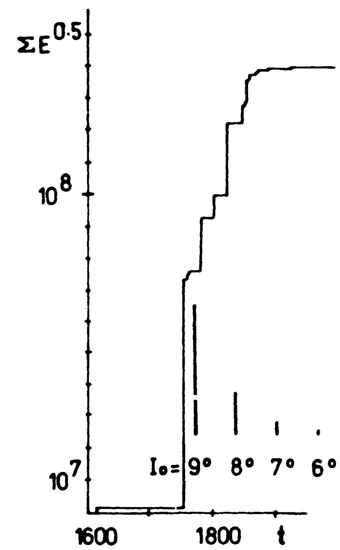

Fig. 17

Benioff graph of the Komárno region, $E[J]$ is energy, t [years] time.

Eastern Slovakia

Data on earthquakes in Eastern Slovakia are available since 1605. There exist a total of 64 records. The solitary shock in the area of Rožňava on 23. 1. 1855 may have been connected with mining activity. The foci of shocks are in the area of:

- Spišská Nová Ves and Levoča ($I_0 \leqq 7°$ MSK-64, Vepora deep fault, e.g. 12. 4. 1724, 23. 4. 1840);
- Gelnica and Krompachy ($I_0 \leqq 5°$ MSK-64, e.g. 28. 7. 1703, 10.–13. 3. 1724, some shocks may have been connected with mining activity);
- Slánské hory Mts deep fault (the area of Přerov and Košice, $I_0 \leqq 7°$ MSK-64, e.g. 26. 3. 1676, 17. 11. 1809, 29. 4. 1974, the vicinity of Šariš, 17. 11. 1809, $I_0 > 7°$ MSK-64; foci of the strongest shocks lie on the intersection of the Slánské hory Mts deep fault and the Záhorie–Humenné deep fault);
- Giraltovce, Humenné and Koliabovce ($I_0 \leqq 7°$ MSK-64, foci of the strongest shocks are in the area of Vranov n. Top., which lies on the intersection of the N–S line of foci with the Záhorie–Humenné deep fault; the N–S alignment of foci roughly along the Ondava river has the same direction as the Slánské hory Mts deep fault, which lies about 35 km west this focal line; the N–S line of foci intersects transversely the units of the Carpathians and the lowlands of Eastern Slovakia and Pannonia).

Volyne–Podol highlands

The strongest shock on 17. 8. 1875 ($I_0 = 7°$ MSK-64) was felt macroseismically far in the Russian (East - European) Platform (Procházková, Kárník eds 1978); its focus was connected with a fault parallel to the Teisseyre–Tornquist fault.

Ruthenia

Since 1781, 58 shocks have been recorded in the region of the Soviet Carpathians and the surroundings, i.e. Lvov, Zaleshchiki, Chernovcy ($I_0 \leqq 6.5°$ MSK-64, Teisseyre–Tornquist fault), Perechin, Svaljava, Siget ($I_0 \leqq 7°$ MSK-64, a continuation of the Záhorie–Humenné deep fault) und Uzhorod, Mukachevo, Beregovo ($I_0 \leqq 7.5°$ MSK-64, Számos deep fault). Apart from the shocks connected with the Záhorie–Humenné deep fault and the Számos deep fault, there are shocks here connected with the Tisa river fault (e.g. on 23. 8. 1979). The study area forms a mosaic, the blocks of which adapt themselves at many places relatively easily to changes in the force systems which affect them. The earthquakes are of tectonic origin and block movements with dominant vertical component prevail (Zátopek 1940).

Hungary

Data on earthquakes on the territory of Hungary have existed since 455. Csomor's map of epicenters (Kárník, Procházková, Schenková, eds 1981) only contains foci of 16 shocks with $I_0 \geqq 6°$ MSK-64 in the period 455–1900. The foci lie on important deep faults striking SW–NE:

– Osapod ($I_0 \leqq 5°$ MSK-64).
– Raaba (Koermand, Gyarmat, $I_0 \leqq 8.5°$ MSK-64). The strongest earthquake was on 10. 7. 445 in Szombathely Aquinicum. The foci of shocks in areas Diojenoe, Ersekvadken, Balassgyarmat and in Štúrovo, Rimavská Sobota, Šafárikovo are on the continuation of the Raaba deep fault. The Komárno area characterized by deeper shocks were described earlier.
– Bakonyi Forest ($I_0 \leqq 8.5°$ MSK-64).
– Balaton–Darno (Nagykanisza, Dunaharaszti, Kacinczbarcika, $I_0 \leqq 8.5°$ MSK-64, the foci of strongest shocks were south of Budapest and Miskolc).
– Zagreb–Zemplín (Kaposvár, Dunaváros, Tokaj, $I_0 \leqq 7.5°$ MSK-64). The strongest shocks in Central Hungary occur in the region of Jászberény, which lies on the intersection of fault Zagreb–Zemplín with the fault system of Central Slovakia. Foci in the area of Zemplín and Čierná n. Tis. probably lie on the continuation of this fault.
– Szolnok–Ebes (Pécs, Keczkemet, Szolnok, $I_0 \leqq 9.5°$ MSK-64). Foci of the strongest shocks are in the Keczkemet region. Both regions Pécs and Keczkemet are distinguished by rapid subsidence at the recent time.
– Mohácz–Koeroes (Mohácz, Csongrád, Gyoma, $I_0 \leqq 6°$ MSK-64).

These faults are in direct connection with the confinement of individual blocks of the Mesozoic underlying rock and are related to the structures of the Western Carpathians. A lot of foci lie on the SE margin of the Bakonyi Forest and on its continuation towards NNE, where they are likely to be connected with the fault system of Central Slovakia. Foci of the strongest shocks lie on the intersection of deep faults, e.g. the focus of the earthquake of 12. 1. 1956 lay on the intersection of deep fault Balaton–Darno and on the continuation of the N–S fault system of Central Slovakia; the focus of the earthquake of 19. 2. 1951 lay on the intersection of deep fault Raaba and the N–S fault system of Central Slovakia. A relatively great intensity attenuation in the Pannonian Basin in the case of shallow shocks can be accounted for by a thick layer of Tertiary sediments (1000–6000 m).

Border region of Hungary and Roumania

The earthquakes ($I_0 \leqq 8.5°$ MSK-64, $h < 25$ km) are connected with the western boundary fault of the Apuseni Mts.

Roumania

In Roumania, no data on weak shocks are available until the 20th century. Foci lie in the Eastern and Southern Carpathians, Transylvania, Banat, Crishane, Maramuresh and Bukovina ($I_0 \leqq 8°$ MSK-64). The most active region in respect of earthquake occurrence is region Vrancea (shallow shocks $h = 30-45$ km, $I_0 \leqq 6°$ MSK-64; intermediate shocks $h = 70-160$ km, $I_0 \leqq 9°$ MSK-64). Here foci of shocks lie on a deep fault of the NE–SW direction, which, according to

Belyayevski is associated with the mantle elevation beneath the Black Sea. The direction of its north wing is NE – SW and it coincides with the MOHO subsidence towards SW under the Eastern Carpathians and the platform margin. In the wider surroundings of the Vrancea region there is a contact of different tectonic units, namely, the Eastern Carpathians, the Moesian Platform and the East - European Platform, which makes us assume that the wing of the mantle elevation is deep – tectonized and may bear signs of the Wadati – Benioff zone. It is a geologically young deep tectonic direction, also manifest in the directions of recent elevations and depressions. The higher intensity attenuation established in shallow shocks in the Pannonian Basin is not manifest in this case, which means that the properties of the deeper underlying rock are different from those of the surface parts. For intermediate earthquakes the relationships $\log M_0 = (8.98 \pm 0.80) + (1.5 \pm 0.10) M$ for $M = 5.2 - 7.4$ holds; M_0 [N.m] is the seismic moment and M is the surface wave magnitude. An analysis of source parameters showed that two types of earthquakes occur there; we can observe a low stress drop (e.g. 10. 11. 1940) and a high stress drop (4. 3. 1977) earthquakes with near the same surface wave magnitude. After earthquakes with a high stress drop only relatively weak aftershocks and a relatively small number of aftershocks are observed.

The earthquake on 4. 3. 1977 also caused relatively much damage, which corresponds to the hypothesis of Hanks (1979) and Mori (1983), according to which ground acceleration under an earthquake is proportional to the stress drop. The last two strong earthquakes on March 4, 1977 and on August 30, 1986 were felt on the territory of Czechoslovakia (Radu et al. 1979, Procházková, Brouček 1989). Figure 18 shows the seismogram of the earthquake on Aug. 30. 1986 recorded by the low – sensitivity channel of the SVKD seismograph (vertical component); we can see that the onsets of the P and S waves are very clear.

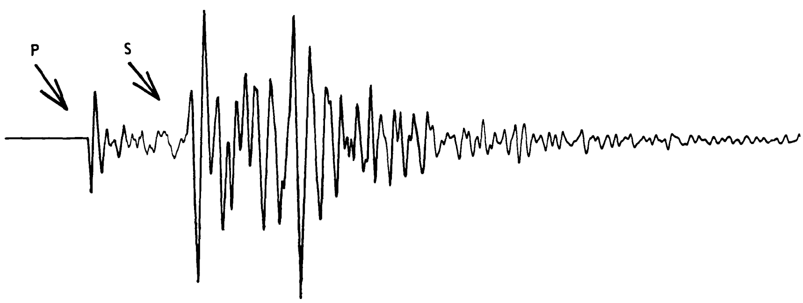

Fig. 18

Seismogram of the Vrancea earthquake of Aug. 30, 1986 recorded at the seismographic station Průhonice. Onsets of the P and S waves are marked. A low – sensitivity channel of the SVKD seismograph, vertical component.

Mur, Muerz, Leitha

Earthquakes ($I_0 \leqq 8°$ MSK-64) are connected with presumed deep fault Mur, Muerz, Leitha. This line of foci continues farther to the Little Carpathians, where it is connected with the Záhorie—Humenné deep fault. If we included region Villach, we would get max $I_0 = 11°$ MSK-64. The earthquakes of the Eastern Alps mostly distinguished by an anomalous shape of the macroseismic field, they are strongly felt in the area of the Bohemian Massif while in the direction of the Pannonian Lowlands and the Carpathians, intensities drop very fast, e.g. Fig. 19. This fact is exaplained either as a result of the seismic energy being conducted through the block structure or as due to the non-symmetric structure of the Alps body. Some of stronger shocks with epicenter intensities of about 8° MSK-64 with

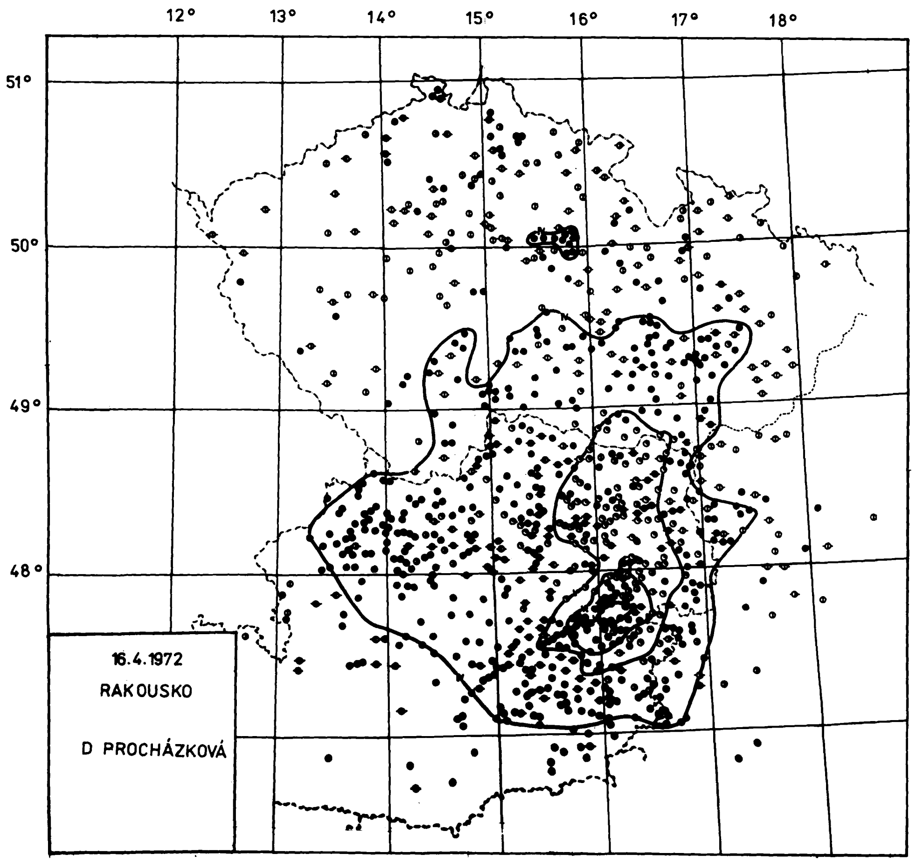

Fig. 19

Isoseismal map of the earthquake in the Eastern Alps on April 16, 1972, 10h00m05s UTC, $I_0 = 7.75°$ MSK-64.

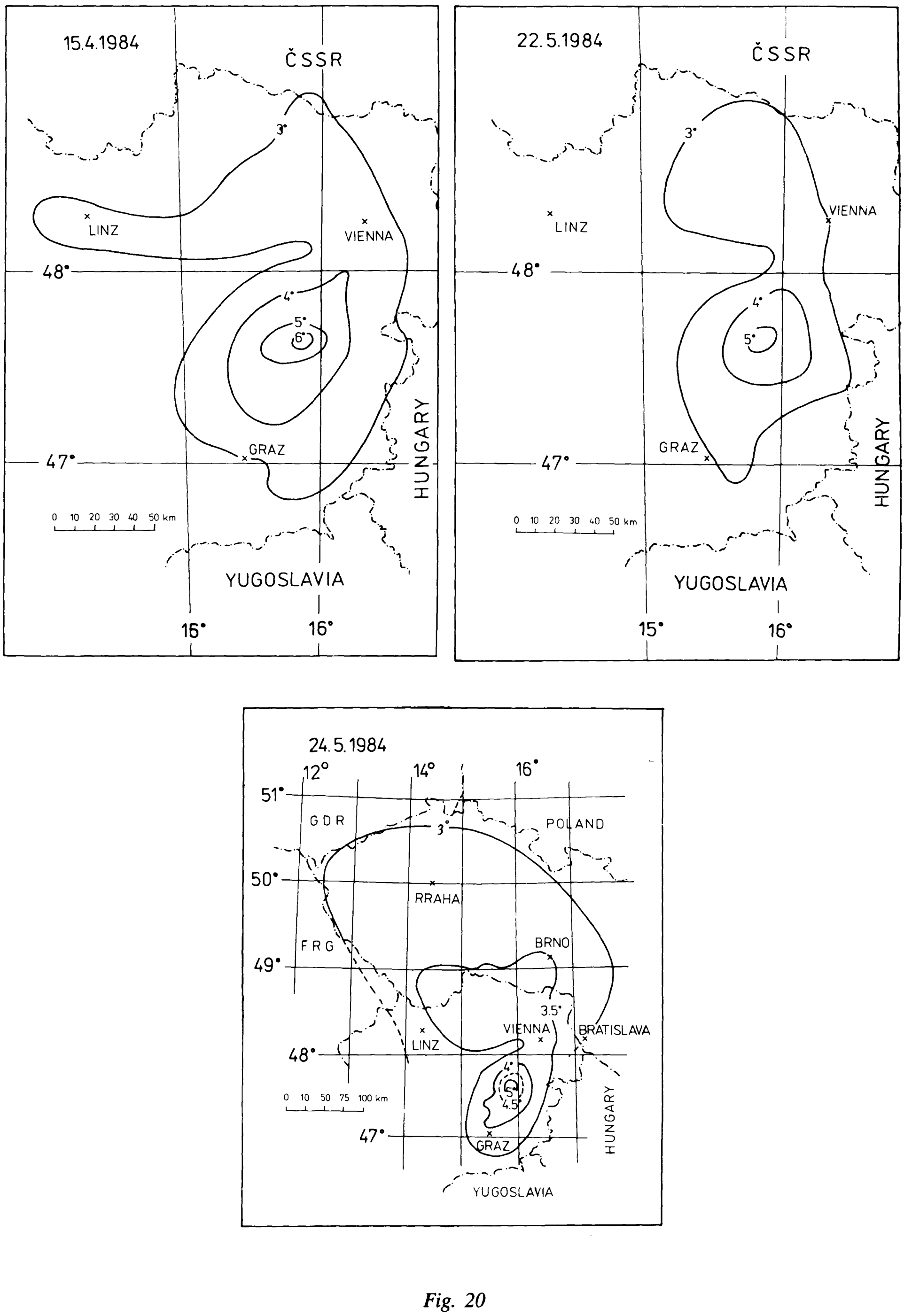

Fig. 20

Isoseismal maps of earthquakes in region Semmering of 15. 4. 1984, 22. 5. 1984, 24. 5. 1984.

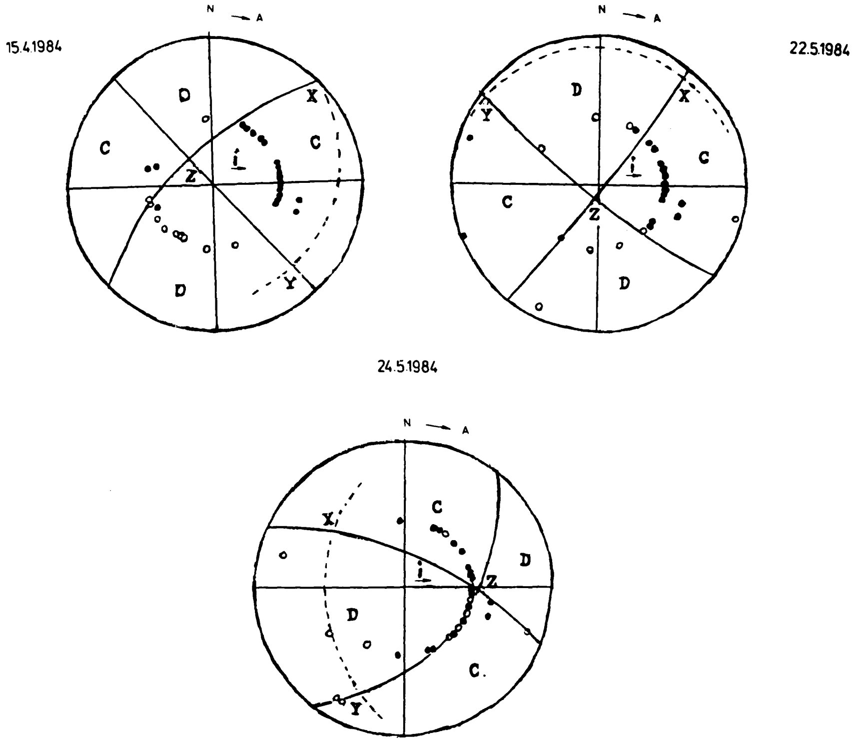

Fig. 21

Focal mechanisms of earthquakes in region Semmering of 15. 4. 1984, 22. 5. 1984, 24. 5. 1984.

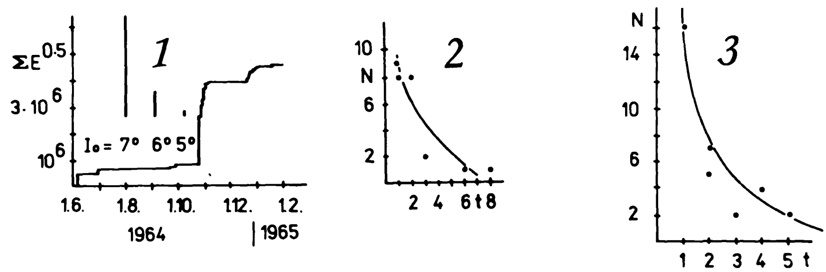

Fig. 22

Quantitative characteristics of selected earthquakes in the region of Mur, Muerz, Leitha:

1 — Benioff graph of earthquakes in region Wiener Neustadt in the period 1. 6. 1964 — 1. 2. 1965. $E[J]$ is energy and t [day] time. In graph individual earthquakes are not denoted by means of independent $E^{0.5}$. In each time unit [day], we give the sum $E^{0.5}$ of earthquakes which originated since the beginning of the selected time period to date.

2 — Dependence of aftershock number N on time t measured from the main shock on 27. 10. 1964 in region Semmering, $[t]$ = days.

3 — Dependence of aftershock number N on time t [days] measured from the main shock on 16. 4. 1972 in the Seebstein region.

foci in the Eastern Alps or in the Alps foothill belt are macroseismically manifest as far as Dresden, more distinctly in mobile zones, whose position is connected with the dominant fault belts of the Bohemian Massif, with gravimetric and geomagnetic anomalies and with a deflection of the vertical (Zátopek 1948). A systematic local intensity increase is also observed in the regions, where the sedimentary Quaternary cover attains in the Bohemian Massif a thickness of 30 – 50 m. In the past, the effects of these shocks were studied by e.g. A. Kowatsch, F. Heritsch, A. Koláček, F. Kaütský, R. Schwinner, A. Sieberg, A. Zátopek. Shocks with $I_0 \geqq 5.5°$ MSK-64 in the area of Wiener Neustadt and north of it are felt in the territory of Czechoslovakia. The focal depths of earthquakes are 1 – 18 km; for stronger shocks with $I_0 \geqq 5.5°$ MSK-64, the typical focal depth is 7 km.

A group of earthquakes occurred in the Semmering region in 1984. For three strong shocks on Apr. 15, 1984 10h56m52.4s UTC, $M_L = 4.7$, May 22, 1984 19h33m32.2s UTC, $M_L = 3.8$, and May 24, 1984 19h56m05.9s UTC, $M_L = 4.6$, the isoseismal maps and the focal mechanisms were determined, Figs. 20 – 21. We can see that the shocks differed in the elongation of isoseismals, partly also in the local intensity anomalies as well and in earthquake mechanisms (similar in the first two shocks and quite different in the third shock). This reality indicates the hypothesis that in the Bohemian Massif earthquakes with foci in the Semmering region with a mechanism corresponding to the motion of blocks in the SE – NW direction are felt much farther than earthquakes with a mechanism indicating a motion of blocks in the SW – NE direction.

Two or three stronger shocks in one sequence are observed in the Semmering region from time to time, see the Benioff graph in Fig. 22. The aftershocks sequences after stronger shocks usually last several days, see Fig. 22 – graphs no. 2, 3.

The earthquake of 25. 1. 1348 in the region of Villach is regarded as the largest historical earthquake in Central Europe. Villach was totally destroyed, Dobrač collapsed, water overflowed the banks of the Gail river and flooded the valley, about 5000 persons perished. In South Bohemia and South Moravia, intensities attained 5 – 6° MSK-64.

Central, Western and Southern Alps

In Austria, foci of strong shocks occur further in the regions of the rivers Inn, Saalach, Salzach, Enns, Drau. The earthquakes in the Innsbruck region ($I_0 \leqq 8°$ MSK-64) are connected with the Central Alpine fissure; on the territory of the ČR the shocks of epicentral intensity $I_0 \geqq 7.5°$ MSK-64 are felt. The shocks in the region Admont, Scheibbs, Neulengbach ($I_0 \leqq 9°$ MSK-64) may be the question of a fault parallel to the presumed Mur, Muerz, Leitha fault, which runs in the basement covered with overthrust outer belts of the Eastern Alps (flysh zone and Northern Limestone Alps). Like the Mur, Muerz, Leitha line, this line runs obligue to Alpine structures. Some earthquakes, e.g. on 22. 3. 1907 near Admont, lie the

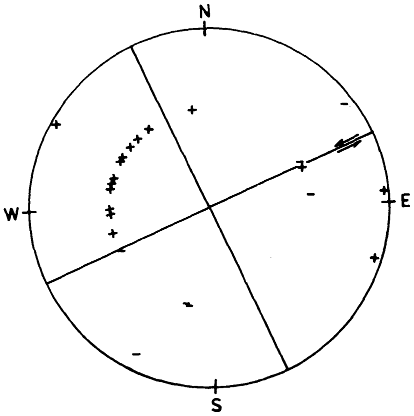

Fig. 23
Fault – plane solution of the earthquake in Northern Styria on April 14, 1983.

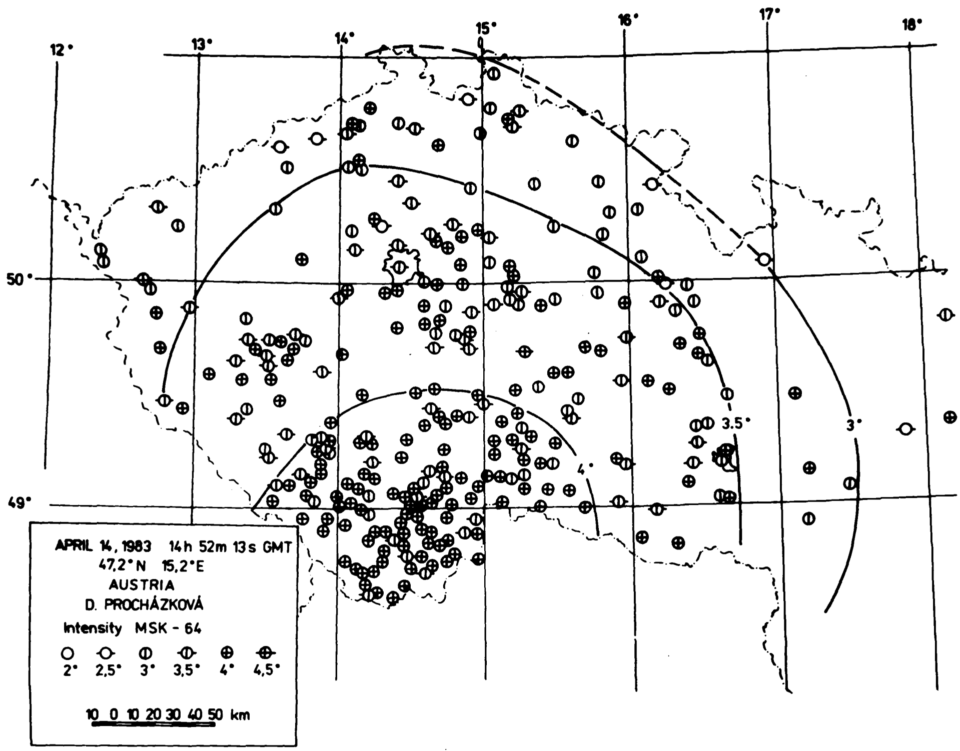

Fig. 24
Isoseismal map of the earthquake in Northern Styria on April 14, 1983 (detail – ČR).

intersection of the E – W structural elements with the well-known Diendorf fault, which continues from the deep underlying rock, and was identified by Tolmann on the basis of a study of satellite images. Earthquakes ($I_0 \leqq 6.75°$ MSK-64) also occur from time to time in the region St. Martin, Molln. The last stronger earthquake occurred in the region of Scheibbs on April 14, 1983 at 14h52m13s UTC, $M = 4.5$. Figure 23 shows the fault – plane solution of this shock and Fig. 24 shows the isoseismal map (Drimmel, Procházková 1985). It was characterized by very good propagation of the macroseismic effects to the north and north-west of the epicentre and, on the other hand, by the quick damping of the macroseismic phenomena to the south and east; this anomalous nature of the macroseismic field is typical of East - Alpine earthquakes.

On the Czechoslovak territory there were also felt shocks of the area of Basel (12. 5. 1021 – $I_0 = 8°$ MSK-64, 18. 10. 1350 – $I_0 = ?$, 1. 6. 1372 – $I_0 = 9°$ MSK-64), Central Switzerland (8. 9. 1601 – $I_0 = 9°$ MSK-64) and SW Switzerland – the area of Wallis (25. 7. 1855 – $I_0 = 8.5°$ MSK-64).

The area of Italy belongs to the most active parts of Europe. Foci of strong earthquakes with $I_0 \geqq 8°$ MSK-64 occur throughout the Apennine Peninsula. As regards our study region, in North Italy there are most active regions which are also the sites where foci of the strongest earthquakes lay; it is the area in the surroundings of Lago di Garda (NE of the town of Brescia) where faults Brescia – Friuli – Villach ($I_0 \leqq 11°$ MSK-64) and Verona – Padua ($I_0 \leqq 9°$ MSK-64) intersect, and the Friuli area, which is on the intersection of the Friuli – Villach fault with the central Alpine scar. Earthquakes, whose foci lie in the Cremona – Verona – Belluno zone, manifest themselves by macroseismic effects in Czechoslovakia (e.g. 6. 5. 1976). The 1976 sequence was very well documented; Figure 25, graphs nos 1 and 2, shows two active periods, graph no. 3 shows the quietening of the seismic activity of the region in the years 1976 – 1981.

Earthquakes in Northern Yugoslavia are connected with the fault of the Sava river ($I_0 \leqq 10°$ MSK-64, Ljubljana, Zagreb, Slavonski Brod, $h < 20$ km and with the fault of the Drava River ($I_0 \leqq 8°$ MSK-64, $h \leqq 40$ km). Deeper shocks in area Ljubljana, Zagreb, Slavonski Brod occur in the east part of the area; the shallowest shocks are in the Legrad area at the border between Yugoslavia and Hungary. On the territory of Czechoslovakia there were macroseismically felt the shocks of areas:

- Ljubljana (29. 3. 1000 – $I_0 = 8°$ MSK-64, 26. 3. 1511 – $I_0 = 9.5°$ MSK-64, 14. 4. 1895 – $I_0 = 8.5°$ MSK-64),
- Zagreb (9. 1. 1880 – $I_0 = 9°$ MSK-64),
- Slavonski Brod (13. 4. 1964 – $I_0 = 8°$ MSK-64).

Remarks:

Moreover on the Czechoslovak territory there were felt strong earthquakes of the Rhine valley (19. 2. 1620, 2. 10. 1869) and even of Monte Negro (15. 4. 1979 – $I_0 = 9.5°$ MSK-64).

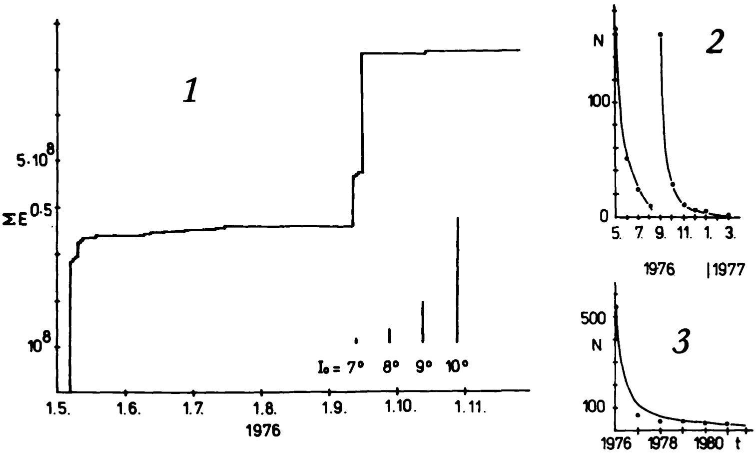

Fig. 25

Quantitative characteristics of the 1976 earthquake sequence in the Friuli region:
1 — Benioff graph for earthquakes in region Friuli in 1976. Individual earthquakes are not denoted by means of independent $E^{0.5}$. In each time unit [day], we give the sum $E^{0.5}$ [$J^{0.5}$] of earthquakes which originated since the beginning of the selected time period to date.
2 — Monthly number of shocks N in region Friuli in the period May 1976—March 1977.
3 — Yearly number of shocks in region Friuli in the years 1976—1981.

6.2 Microearthquakes

In regions with a low level of seismicity, which the study area belongs to, new findings on seismicity and its development in time and space can only be obtained through studies of microearthquakes. Seismographic stations equipped with sensitive seismographs record a great amount of weak seismic events; for instance, permanent seismographic stations of the Geophysical Institute of the Czechosl. Acad. Sci. in Průhonice (PRU) and Kašperské Hory (KHC) record monthly 150 to 500 weak near seismic events. Most of them are due to industrial explosions, a part of them to induced earthquakes (mainly rockbursts), and some may be weak tectonic earthquakes in the Bohemian Massif and its proximity. By means of the data of the network of seismographic stations in Central Europe a lot of these shocks can be localized (Knaislová et al. 1988, Procházková 1991a). If the data of this network of stations are combined with those of a local station or of the whole network of local stations, microearthquakes can be well observed.

A special study of microearthquakes in the territory of Czechoslovakia and its proximity is so far conducted only in selected focal regions of tectonic earthquakes, namely in:
- Vogtland, first of all with the help of the network of local stations in the territory of the GDR: Plauen (PLN), Klingenthal (KLI), Bad Elster (BDE) and

Eubabrunn (EUB) (Neunhoefer, Gueth 1983, 1984, Procházková 1984, 1991a). The given seismographic stations have been in operation since 1968.

- The region of Komořany, Most, Hora Svaté Kateřiny, Hora Svatého Šebestiána, first of all with help of seismographic stations Vysoká Pec (VP) since 1982 and Jezerka (JZ) since 1988 (Tobyáš, Procházková 1989, Procházková 1991b).
- The region of Northeast Bohemia, first of all with the help of the seismographic station in Úpice (ÚP) (Procházková, Michek, Tobyáš 1989, Procházková 1991a) since 1986.

The local microearthquakes indicate that tectonic stresses are always released after as longer period of calm (several weeks or months) in the form of individual shocks or earthquake swarms; i.e. the origin of microearthquakes is not even in time, either.

In region Komořany, Most, Hora Svaté Kateřiny, Hora Svatého Šebestiána, seismological measurements made in the years 1982–90 allowed us to infer the relation of the present seismic regime to the earlier activity with macroseismic manifestations. The connection was studied with the use of the generally valid empirical relation between the frequency logarithm of events and the magnitude.

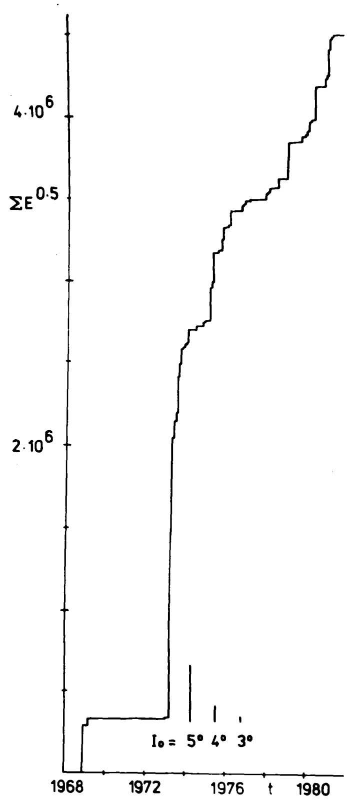

Fig. 26

Benioff graph for microearthquakes in the region Aš-Skalná-Kraslice-Bad Elster-Selb in 1968–83. Individual earthquakes are not denoted by means of independent $E^{0.5}$. In each time unit [year], we give the sum $E^{0.5}$ [$J^{0.5}$] of earthquakes which originated since the beginning of the selected time period to date.

For 43 earthquakes of the years 1784–1910 with magnitudes between 2.4.–4.6 (epicentral intensity 3°–6.5° MSK-64), the statistical model of earthquake occurrence is in very good agreeement with observations. The cumulative frequencies extrapolated to the realm of weaker microearthquakes and transferred to shock occurrences in a year, agree generally with observations from the period of monitoring microearthquakes (Tobyáš, Procházková 1988). It can thus be inferred that at the present time, the character of the process of releasing tectonic energy has not changed, i.e. the origin of relatively strong local earthquakes cannot be precluded.

The study of microearthquakes in region Aš, Skalná, Kraslice, Bad Elster, Selb with the use of the data of the GDR array, KHC, PRU, BRG, VP and MOX (Procházková 1988a) shows that in the realm of microearthquakes there are also active and quiescent periods, see the Benioff graph in Fig. 26. The swarms of microearthquakes like the swarms of earthquakes in this region usually follow longer periods of quiescence and begin with stronger shocks. The recovery after swarms that contain stronger shocks, recorded macroseismically, last several years.

6.3 Typical characteristics of focal regions

The analysis of the quantitative earthquake characteristics (Procházková 1984, 1988b, 1990b) shows that even in a single focal region, earthquakes differ in size, mechanism, focal depth and source dimension. According to the current theory (e.g. Brune 1968), the focal dimension is linked with the stress drop under a shock. It appears that it is the stress drop ($\delta\sigma$) which is the parameter that determines the nature of the group of subsequent shocks. It can be instanced by the following cases:

Vrancea 10. 11. 1940, $M = 7.4$, $\delta\sigma = 1.10$ MPa,
aftershocks lasted until 1943,
4. 3. 1977, $M = 7.3$, $\delta\sigma = 4.5$ MPa,
a small number of weak aftershocks (Fuchs et al. 1979),
Friuli 6. 5. 1976, $M = 6.4$, $\delta\sigma = 0.1$ MPa,
many aftershocks, the strongest with $M = 5.0$, the aftershock serie lasted about 4 months,
15. 9. 1976, $M = 6.1$, $\delta\sigma = 2.4$ MPa,
rapid drop of aftershock activity, Fig. 25, graph no. 2.

In this chapter our attenuation is mainly concentrated on the regions, for which extensive data sets are available. Here it seems that we can define certain typical characteristics properties for each focal region.

Table 3 contains the parameters e, f from relation $\log N_c = e - fI_0$ of selected dependences for the basic geological units. The values of these parameters document the characteristic differences between the individual regions in the study

TABLE 3.
Numerical values of parameters e, f of relationship $\log N_c = e - f I_0$,
σ — standard deviation,
r_k — correlation coefficient.

Region Period	e	f	σ	r_k
Aš – Skalná – Kraslice 1881 – 1983	5.83 ± 0.17	0.76 ± 0.03	0.13	−0.993
Bohemian Massif 1881 – 1983	5.85 ± 0.20	0.74 ± 0.04	0.17	−0.990
Little Carpathians 1881 – 1983	3.21 ± 0.14	0.36 ± 0.02	0.10	−0.989
Ruthenia 1881 – 1983	3.80 ± 0.23	0.44 ± 0.04	0.06	−0.993
Western Carpathians 1881 – 1983	4.33 ± 0.23	0.49 ± 0.04	0.16	−0.985
Bavaria 1870 – 1979	3.08 ± 0.21	0.42 ± 0.04	0.14	−0.976
Hungary 1859 – 1982	4.12 ± 0.02	0.44 ± 0.01	0.02	−0.998
Western Carpathians + Pannonian Basin 1881 – 1982	4.62 ± 0.04	0.48 ± 0.01	0.03	−0.997
Vrancea, $h = i$ 1901 – 1980	4.25 ± 0.14	0.46 ± 0.02	0.12	−0.992
Mur, Muerz, Leitha 1901 – 1980	5.28 ± 0.18	0.62 ± 0.03	0.04	−0.994
Eastern Alps (∅ = 46.7° N) 200 – 1981	5.54 ± 0.07	0.47 ± 0.01	0.07	−0.996
1900 – 1981	5.52 ± 0.12	0.56 ± 0.02	0.11	−0.992
Friuli 1930 – 1976	4.50 ± 0.19	0.45 ± 0.03	0.18	−0.987
Slovenia 1895 – 1981	5.86 ± 0.21	0.67 ± 0.03	0.15	−0.994

area. A description of the regions by means of cumulative frequency is more appropriate because the points lie closer to a straight line on a logarithmic scale than it is the case with simple frequency, Fig. 27. The numerical parameters of the observed dependence vary within fairly wide ranges, similar to our observations in the region the Mediterranean (Procházková 1976) and in the Balkans (Kárník, Procházková 1976b). The value of parameter $f = 0.74$ for the Bohemian Massif is given by the high value of f in region Aš, Skalná, Kraslice, Bad Elster, Selb. If we exclude this region, we obtain value $f = 0.43$. These space distribution of f then indicates that the values of f grow roughly from the north to the south. The application of laboratory results (Scholz 1968, Mogi 1967, Wyss 1973) leads to the conclusion that the stress in the source region in the northern part is higher than in the southern part.

A total of 57 Benioff graphs were constructed for the study area (Procházková 1984, 1988b); examples are presented in Fig. 28. From their comparison it ensues that focal regions do not only differ by the character of active periods, but also by the duration time of active and quiescent periods. The time of energy cumulation is usually longer than that of energy release. The duration time of active periods is several years to tens of years (e.g. focal regions in the Bohemian Massif) up to several centuries (e.g. region Verona, Padua). It is very likely that also the duration time of active periods in one focal region will not be always the same; in the event the energy is released under one relatively very strong shock for the conditions of the region, it will be substantially shorter than if the accumulated energy is released in the form of several strong shocks.

Benioff graphs (Procházková 1984, 1988b) also show e.g. that the most active part of region Mur, Muerz, Leitha is the section Leoben, Wiener Neustadt. Active periods in regions Murrau, Strassburg; Strassburg, Judenburg; Leoben, Wiener Neustadt; Schwadorf do not set in simultaneously, and as a rule, their character is not identical. For instance, one active period began in region Leoben, Wiener

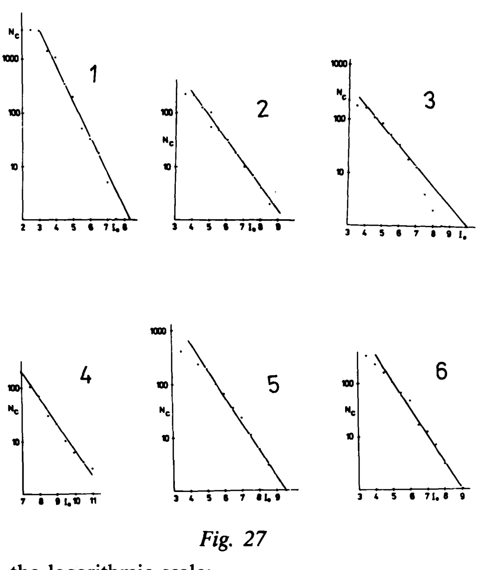

Fig. 27

The relationship $N_c(I_0)$ in the logarithmic scale:

1 – Bohemian Massif, 1881–1983.
2 – Hungary, 1859–1982.
3 – Western Carpathians (Slovakia, southern Poland, Ruthenia), 1881–1983.
4 – Eastern Alps, $I_0 \geqq 7°$ MSK-64, 200 – 1981.
5 – Western Carpathians and Pannonian Basin, 1881–1982.
6 – Vrancea, $h = i$, 1901–1980.

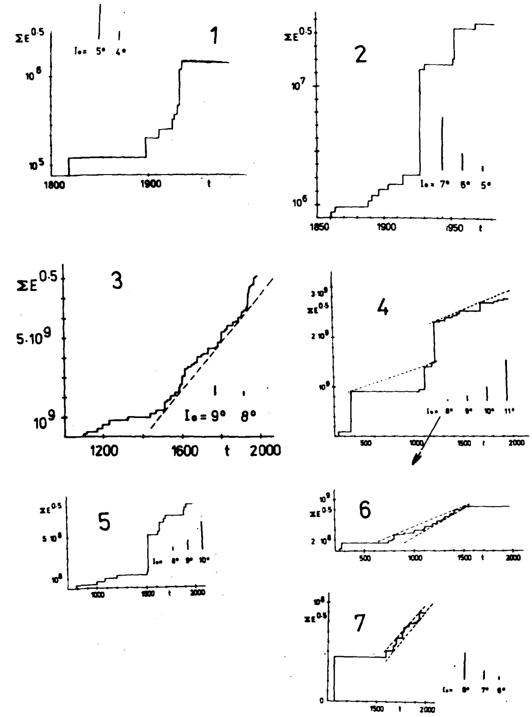

Fig. 28

Benioff graphs of selected focal regions of Central Evrope:

1 – Southern Bohemia,

2 – Bakonyi Forrest,

3 – Vrancea, $h = i$,

4 – Brescia, Lago di Garda,

5 – Slovenia,

6 – Verona, Padua,

7 – Bavaria,

8 – Eastern Alps ($I_0 \geqq 7°$ MSK-64).

In graphs individual earthquakes are not denoted by means of independent $E^{0.5}$ [$J^{0.5}$]. In each time unit [year], we give the sum $E^{0.5}$ of earthquakes which originated since the beginning of the selected time period to date.

Neustadt in 1876, in region Schwadorf in 1885, and in the region of the Little Carpathians in 1890. The mentioned active period in region Leoben, Wiener Neustadt is concentrated round a strong shock in Kindberg ($I_0 = 8°$ MSK-64). The active period in region Schwadorf contained the strong shock of 8. 10. 1927 ($I_0 = 8°$ MSK-64). The active period in the region of the Little Carpathians contained the strong shock of 9. 1. 1906 in the Dobrá Voda ($I_0 = 8°$ MSK-64).

Since in the territory of Central Europe data on weaker earthquakes have been available only in 20th century, earthquake groups and their properties can be actually observed on the basis of the data of this century. The material provided us with

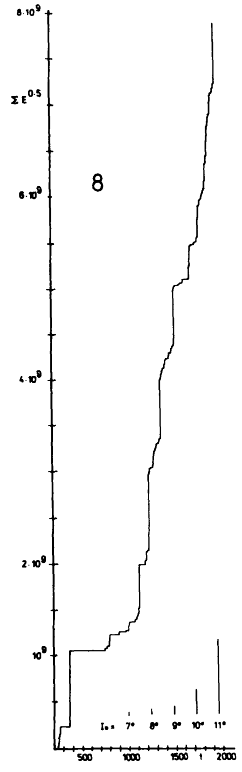

Fig. 28
Continuation.

the possibility to study closely the properties of earthquake swarms in region Aš, Skalná, Kraslice, Bad Elster, Selb (Procházková 1988a, b), and the properties of aftershocks, foreshocks and multiple shock sequences groups, Table 4. The Table 4 makes it evident that as a rule, foreshocks occur right before the main shock. Aftershocks last several days to several months. In the event of very strong shocks (I_0 > 9° MSK-64), increased earthquake activity and very often also aftershocks last a number of years. In the case of stronger main shocks, the strongest aftershocks usually occur sooner after main shock than in the case of weaker main shocks. The number of aftershocks drop with the time measured from the main shock. In the Eastern Alps and in the region Mur, Muerz, Leitha there are two types of shock groups; examples are presented in Table 5. The first type is predominant. The other type has its strongest aftershock substantially weaker than in the former case under an equally strong main shock, and this aftershock occurs distinctly later. As both these types occur in the same places, we can assume that the causes of their differences are not the diversities in the macrostructure of entire

TABLE 4.

δI_{12} [°MSK-64]	– difference between epicentral intensities of main shocks in a multiple earthquake group,
δt_{12}	– time interval between main shocks of a multiple shock group,
δI_1 [°MSK-64]	= I_0 (main shock) – I_0 (strongest aftershock)
δt_1	= time difference in the origin of the strongest aftershock and the main shock,
δI_2 [°MSK-64]	= I_0 (main shock) – I_0 (strongest foreshock),
δt_2	= the time of the origin of the main shock minus the time of the origin of the strongest foreshock
δI_{DP} [°MSK-64]	– difference in intensities of the strongest aftershock and the strongest foreshock,
δt_{DP}	– time differences in the origins of the strongest aftershock and the strongest foreshock,
τ_s	– time duration of a shock group,
σ	– standard error of dependence,
r_k	– correlation coefficient of dependence.

Region Relation	σ	r_k
Komárno – aftershocks:		
τ_S[year] $= -(0.24 \pm 0.84) + (0.49 \pm 0.11)\, I_0$ (MS) for $I_0 \geqq 5°$ MSK-64	0.41	0.912
Hungary		
$\delta I_1 = -(1.75 \pm 1.27) + (0.50 \pm 0.17)\, I_0$ (MS)	0.46	0.866
Vrancea, $h = i$		
$\delta I = -(2.24 \pm 1.03) + (0.60 \pm 0.16)\, I_0$ (MS)	0.55	0.734
δt_1[days] $= (52.45 \pm 12.36) - (5.94 \pm 1.85)\, I_0$ (MS)	6.94	−0.679
Austria		
$\delta I_1 = -(1.3 \pm 0.9) + (0.5 \pm 0.2)\, I_0$ (MS)	0.63	0.589
δt_1[days] $= (1.8 \pm 1.1) - (0.13 \pm 0.18)\, I_0$ (MS)	0.63	−0.598
Eastern Alps		
$\delta I_{12} = -(2.0 \pm 1.0) + (0.36 \pm 0.1)\, I_0$ (SMS)	0.60	0.603
δt_{12}[days] $= -(3.8 \pm 1.3) + (0.6 \pm 0.16)\, I_0$ (SMS)	0.60	0.835
$\delta I_2 = -(5.0 \pm 0.17) + (0.8 \pm 0.1)\, I_0$ (MS)	0.46	0.641
δt_2[days] $= (1.8 \pm 0.5) - (0.16 \pm 0.08)\, I_0$ (MS)	0.38	−0.624
$\delta I_1 = -(1.2 \pm 0.2) + (0.5 \pm 0.04)\, I_0$ (MS)	0.56	0.873
δt_1[days] $= (1.4 \pm 0.3) - (0.13 \pm 0.04)\, I_0$ (MS)	0.30	−0.644
$\delta I_{DP} = (1.6 \pm 0.6) - (0.2 \pm 0.1)\, I_0$ (MS)	0.40	−0.561
δt_{DP}[days] $= -(1.4 \pm 0.5) + (0.36 \pm 0.17)\, I_0$ (MS)	0.45	0.692

MS – main shock,
SMS – the strongest main shock.

focal regions, but they are bound to be linked with the different processes in the earthquake foci themselves.

From Table 4 it also follows that the time between the main shocks in a multiple shock sequence is several days at most, and it is short compared with the duration time of aftershocks. The dependences derived for foreshocks, aftershocks and multiple shock sequences are analogous to the relation derived for Japan, Greece

TABLE 5.
Aftershocks in the Mur, Muerz, Leitha region

1. Shock groups, in which the strongest aftershock follows the main shock within a few hours (up to 1 day), e.g.

date	region	I_0	δI	δt
Dec. 2, 1963	Wiener Neustadt	6.5	2.5	4h
June 30, 1964	Semmering	5.5	2	0.5d
June 2, 1969	Murau	6	1	2.5h
Apr. 16, 1972	Wiener Neustadt	7.75	1.25	1h
Jan. 14, 1978	Semmering	5	1	0.5d
Apr. 14, 1983	Scheibbs	6.5	2	3h

2. Shock groups, in which the strongest aftershock follows the main shock only after a few days, e.g.

date	region	I_0	δI	δt
Oct. 27, 1984	Semmering	6.75	2	27h
Jan. 5, 1972	Wiener Neustadt	6	1	3d
Aug. 6, 1978	Semmering	5	1	7d

Explanations
I_0 – the intensity of the main shock – [° MSK-64],
$\delta I = I_0$ (main shock) – I_0 (strongest aftershock) – [°MSK-64],
δt – the difference in the origin time of the strongest aftershock and the origin time of the main shock,
h – hour,
d – day,

and the region along the Mediterranean Sea; they only differ quantitatively, i.e. in the numerical values of the parameters.

A physical interpretation of the cause of the origin of earthquake groups is very complex. The existing attempts known from the literature start from assumptions based on the mechanical models of the focal region, which are considerably simplified (homogeneous medium, undisturbed medium, simple stress field, non--rheological material parameters, etc.). To devise an adequate physical theory, at the present stage of research, it is essential to investigate the focal parameters which yield some information and classification of focal processes in different places and different time periods.

Within a certain source region, but also within a wider area comprising more regions, earthquakes migrate (Procházková 1984, 1988b, 1990b). Activity in one region often means quiescence in the neighbouring region. This phenomenon can be proved with a different degree of conclusive evidence; Fig. 29 contains examples. Migration testifies to a redistribution of the stress in the lithosphere, usually released due to a strong earthquake in a certain area volume. We can also

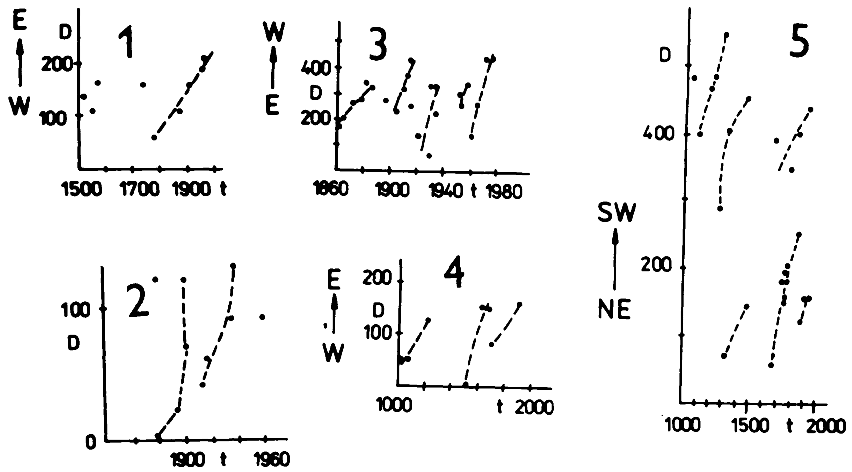

Fig. 29

Migration of earthquake foci, D [km] vs. t [years].
1 – Transylvania $L' = 24°$ E → $26°$ E;
2 – Banat $\Phi = 45.8°$ N → $46.1°$ N;
3 – Vicinity of Innsbruck $L' = 14°$ E → $9°$ E;
4 – Slovenia $L' = 14°$ E → $16°$ E;
5 – Friuli-Villach [46.8° N, 14.4° E] → [45.3° N, 9.6° E].
Orientation of vertical axis is given by the direction of arrow. Curves in the graphs show the time succession.

presume that the earthquakes that belong to one migration cycle have the same cause, are confined to one pressure system, and are interconnected. The fact that there are different migrations of earthquake foci in different focal regions leads to the assumption that the character of the tectonic processes (stress fields) in these regions is not the same.

6.4 Space-and-time pattern

The synthesis of results in Central Europe can be summarized as follows:

- As a rule, earthquake foci are connected with the faults that separate geological units. At the present time, only some parts of faults are seismoactive. The foci of stronger earthquakes frequently lie on the points of intersection of faults, sometimes a shock connected with one fault system is followed by a shock connected with the other fault system. Usually, one fault system is predominant in respect of earthquake occurrence.
- But for some exceptions, earthquake foci occur in the upper part of the Earth's

crust ($h \leqq 10$ km). In the southern part of the study area, the seismoactive layer (i.e. the layer with foci) is thicker than in the northern and central parts.

— Earthquakes originating in a particular area differ in the size, focal depth, mechanism and dimensions of the focus.
— As regards the seismicity character, the study area is greatly differentiated. Seismicity is a function of space and time. The seismic regime in focal regions is variable with time (there occur either active periods or gaps); periods of quiescence may last hundreds, even thousands of years.
— The short-term character of seismic activity is represented by sequences main shock — aftershocks, foreshocks — main shock — aftershocks, multiple earthquake sequences in the case of stronger earthquakes with the exception of region Aš—Skalná—Kraslice—Bad Elster—Selb of which earthquake swarms are typical. Weak earthquakes and microearthquakes occur single or in groups of the swarm type.
— In some focal regions there are indications of the existence of space-and-time tendencies in earthquake occurrence.
— The physical processes taking place in earthquake foci are not identical. Even in one focal region, different processes can be observed in the focus.

7. Conclusion

Endogenous tectonic recent movements, a product of which are also earthquakes, have an appreciable time and regional stability, and therefore, they can be supposed to go on (continuously or intermittently) even in the historical future. If they manifested themselves as seismogenic in the past, we can presume that their character will hardly change in a natural way in the future, measured by the time scale corresponding to the life of several generations. If we know the movements as being antiseismic, much depends on the length of the historical observation period; safety has invariably historical limitations. The lithosphere development in the geological time scale evidences possibilities of very essential changes in the tectonic regime; of course, it also evidences its great stability by the human history standards.

The existence of a great variety of time — space models of earthquake occurrence, by which the group of focal regions in the study area is distinguished, the fact that in none of these focal regions the same types of earthquake activity repeating regularly have been found as yet, and also the idea of rock massifs as wholes in the time — variable stress field, thus constantly changing and developing, lead to a sceptical conclusion on the possibility of a reliable short-term earthquake prediction in the study area on the existing findings.

The present work contains:

— A description of the seismicity in individual focal regions, qualitative and in some cases also quantitative characteristics.

– A description of the typical character of earthquake activity of a region with low seismicity.
– Evidences on the differences between earthquake regimes in single focal regions in the study area. Focal regions characterized by close qualitative and quantitative characteristics have formed seismotectonic units in the recent time.
– Evidences on the differences between the earthquakes in single focal regions.

The differences in earthquake regimes are accounted for by the differences in the structures of regions and in focal processes. Although last thirty years have marked a lot of progress in our understanding of the focal processes, the knowledge of the mechanism that generates an earthquake and its changes in space and time is only beginning to be assembled.

In order to acquire further knowledge, we have to built up local networks of seismographic stations and to observe the changes in the dynamic focal parameters with time in individual focal regions, which is the only way of obtaining information on the focal processes that are variable in one place.

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