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NATURAL AND INDUCED SEISMICITY OF THE NORTHWEST BOHEMIA BROWN-COAL DISTRICT AND THE ADJACENT ORE MOUNTAINS

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Abstract: The seismic activity of the region is analysed on the basis of recent microseismic observations. The significant difference in the mean annual frequencies distribution to macroseismic observations as well as the shallow depth explain to an induced character of the recent microactivity in the vicinity of the open-pit mines. In the energy-time history of the last 20 years three phases characterized by a constant and gradual energy release can be distinguished. Together with an increasing trend of b-value a favourable state with regard to seismic risk may be assumed.

Key words: microseismicity, macroseismicity, open-pit mine, Northern Bohemia

1. INTRODUCTION

The area under study is situated in the Northwest Bohemian brown-coal district (approximately within 50.5 - 50.7° N and 13.4 -13.8° E) on the boundary of the North Bohemian Basin to the Ore Mountains crystalline anticlinorium.

In spite of a seismotectonic mobility of the region in the past the recent macroseismic activity is very low; there had been no macroseismic observations since 1910. However, a microseismic activity is traceable by means of recordings of local seismic stations.

The stability of high steep slopes is decreased by stripping a 150 m thick overburden of the brown-coal seam in the basin close by the foothills. Considering the extensive mining exploitation one cannot exclude triggering landslides or rockfalls in case of occurrence of moderate local earthquake.

To investigate relationships between macro- and microseismicity and mining operations with regard to a possible risk factor a systematic observation of current seismic activity is of highly interest.

Two local stations were put in operation in the central part of the region in 1982 (Vysoka Pec VPC) and 1990 (Hora Svate Kateriny HSK). The first and second analysis of the results of 3 and 6 1/4 years of measurements were published in TOBYAS et al. 1987 and TOBYAS, MITTAG 1992. However, a reliable and a long-term analysis of seismicity was only possible by means of complete and homogenous recordings of the near-by highly sensitive standard station at Berggießhübel (BRG). By reinterpretation of a 20 years time interval a data set of 3100 night-time events in the vicinity of the open-pit mines with local magnitudes between 1.2 and 3.1 had been detected.

The new results concerning magnitude-frequency relationship and time variations of tectonic stress release and b-value are dis-cussed in this paper. It
racter of a microseismic activity and the relationship to mining operations only by means of a single near-by standard seismic station.

2. DATA PROCESSING

Macroseismic observations of 44 shallow earthquakes with depth between 6 and 9 km and epicentral intensities from 3° to 6.5° MSK-64 are available in the period 1784-1910 (PROCHAZKOVA et al. 1987). According to the relation valid for the Bohemian Massif

$$M = 0.63*I+0.5 \quad (1)$$

magnitude M was calculated for the epicentral intensity I of the separate earthquakes.

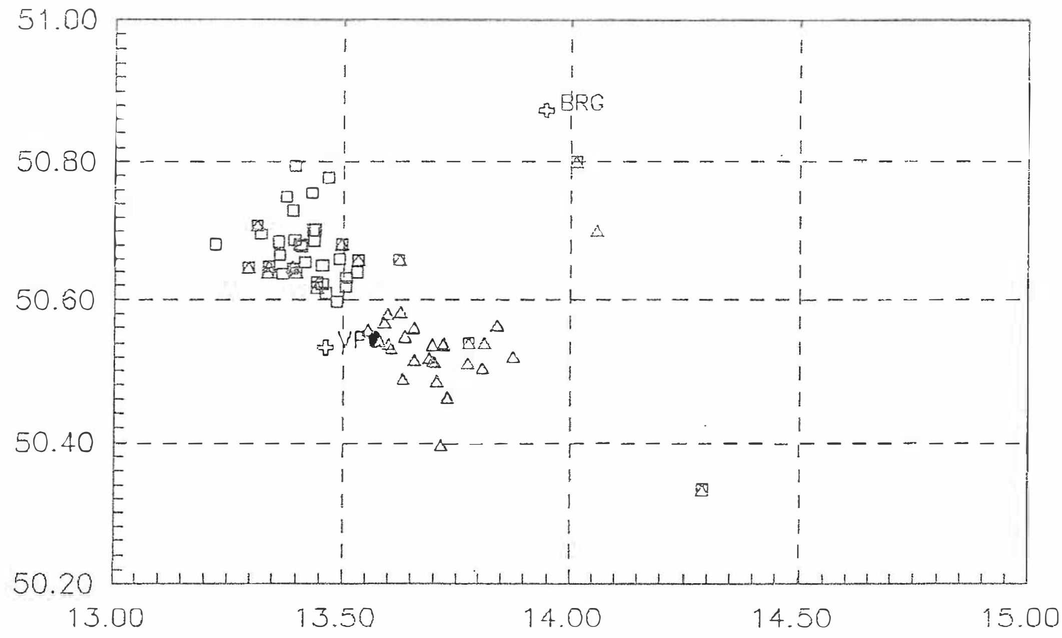

Fig. 1. Epicentres of microevents recorded by two or more stations since 1982.

A first selection in microseismic data processing was based on records of local station VPC and blasts list of mining authorities. To discriminate between the local tectonic and man-made seismic events only the events which occured at night (from 18 to 05 hrs. UTC), when blasting operations in the surface mines are forbidden, were accepted as natural and tectonic origin. The detected tectonic events were analysed by records of neighbouring regional stations. A localisation was possible only for stronger events and can not be more accurate than 2-3 km (STRAUCH 1988). The most localisations were made only with recordings of local station VPC and the nearest regional station BRG . Ambiguous epicentres of the so localised tectonic events are shown in Fig.1 by single squares and triangels, respectively. In case of localisation by more than two stations epicentres are denoted by triangels within squares.

In the course of data processing a pattern recognition for seismogram interpretation of regional station BRG was found to detect tectonic events of the interesting area. So it was possible to eliminate relevant events only by recordings of the nearby and highly sensitive standard station BRG and to expand the observation time interval back to 1972 when continuous seismological observation at this station started.

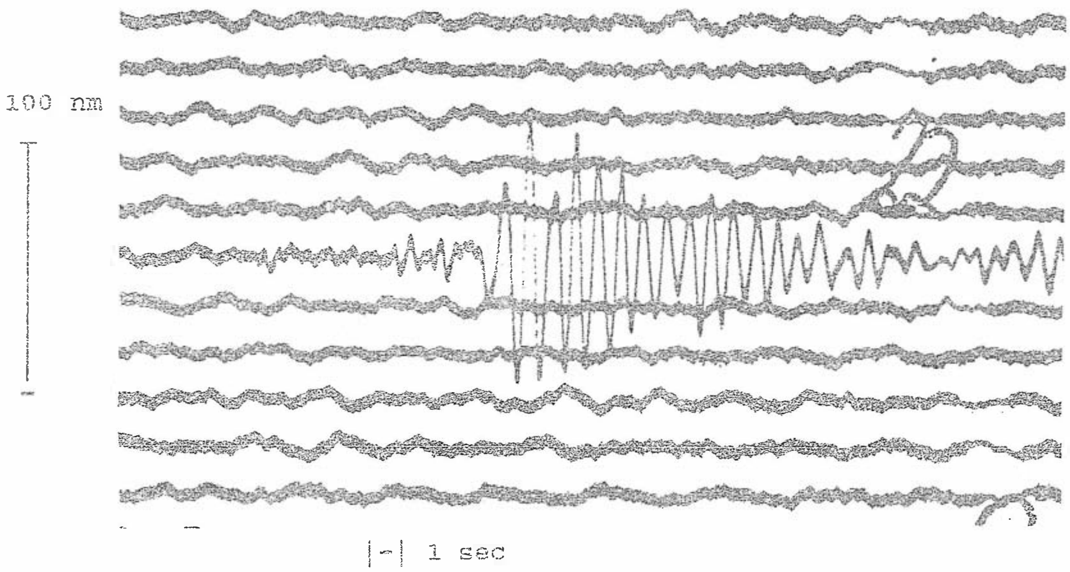

Fig. 2. The strongest microseismic event with M_L=3.1 recorded at BRG by vertical shortperiod seismograph on 1.7.1977 22:29 UT.

A typical seismogram example of microseismic event recorded at BRG is shown in Fig.2. A vertical polarised wave with periods of 0.7-1.2 seconds, identified as Rg-wave (KULHANEK 1990), is predominant. In most cases the Rg-wave was the only interpretable one, so that the size of microearthquakes was classified by the local magnitude of station BRG for surface wave (TOBYAS, MITTAG 1993)

$$M_L = \log A/T + 0.000057*D + 1.039 , \qquad (2)$$

where A is measured in nm, T in sec and D in km, and converted into magnitude consistent with the classification of macroseismic data by relation (TOBYAS, MITTAG 1991)

$$M = -3.2 + 1.45*M_L \quad . \qquad (3)$$

For stronger events amplitude ratio between Rg- and Sg-wave could been calculated as a constant value of about 3.

The continuous and stable recording at station BRG guarantees a complete and homogeneous data set.

3. MAGNITUDE-FREQUENCY-RELATIONS

The observed macroseismic data, listed in PROCHAZKOVA et al. 1987, fit well the relationship between the cumulative frequency N and surface wave magnitude M in the form

$$\log N = 3.27 - 0.67*M \quad . \qquad (4)$$

An equal span of magnitude classes dM = 0.6, corresponding approximately to one unit of epicentral intensity, was used to derive magnitude-frequency distribution. Good approximation of the cumulative frequency by a single linear relation indicates that observations are complete in the given narrow magnitude range and that the events occured in one zone with uniform seismotectonic conditions.

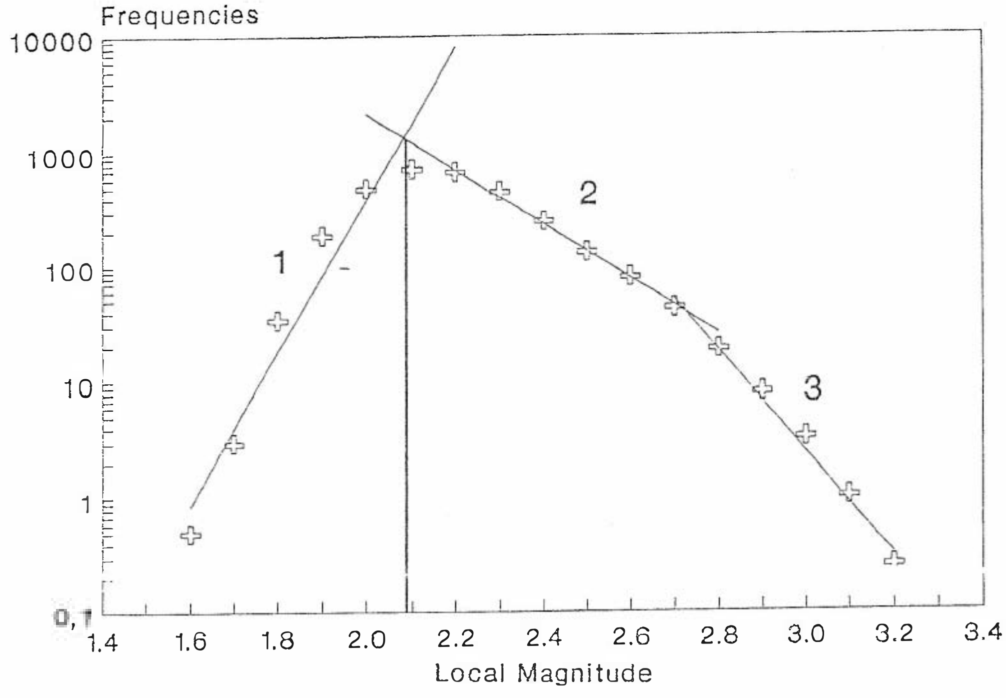

Fig. 3. Single frequencies versus local magnitude. The limit between complete and incomplete data is marked by vertical line.

In relating frequency of microearthquakes to local magnitude M_L a data set of 3100 events was classified into magnitude intervals of 0.1 unit. The frequency values plotted in Fig.3 are obtained as running averages over three consecutive values, separated by 0.1 M_L units, i.e. as $(N_1+2*N_2+N_3)/4$. This smoothing is justified considering M_L. The so obtained magnitude-frequency curve can be approximated by one straight line in the ascenting part (1) and two in the descending part (2 and 3), representing by following equations obtained by least square solutions

$$\text{part 1:} \quad \log N = -10.66(+-1.45) + 6.62(+-0.78)*M_L \, , \qquad (5)$$
$$\text{part 2:} \quad \log N = 8.11(+-0.25) - 2.39(+-0.10)*M_L \, , \qquad (6)$$
$$\text{part 3:} \quad \log N = 13.62(+-0.71) - 4.41(+-0.24)*M_L \, . \qquad (7)$$

Combining equation (5) and (6) the threshold magnitude of M_L=2.08 can be derived; i.e. the observation material can be assumed as complete for magnitudes M_L>=2.08 . The dual behaviour even for M_L>2.08 may be caused by an unsufficient span of observing period or may be a hint to another seismotectonic regime for events with magnitude M_L>2.73 .

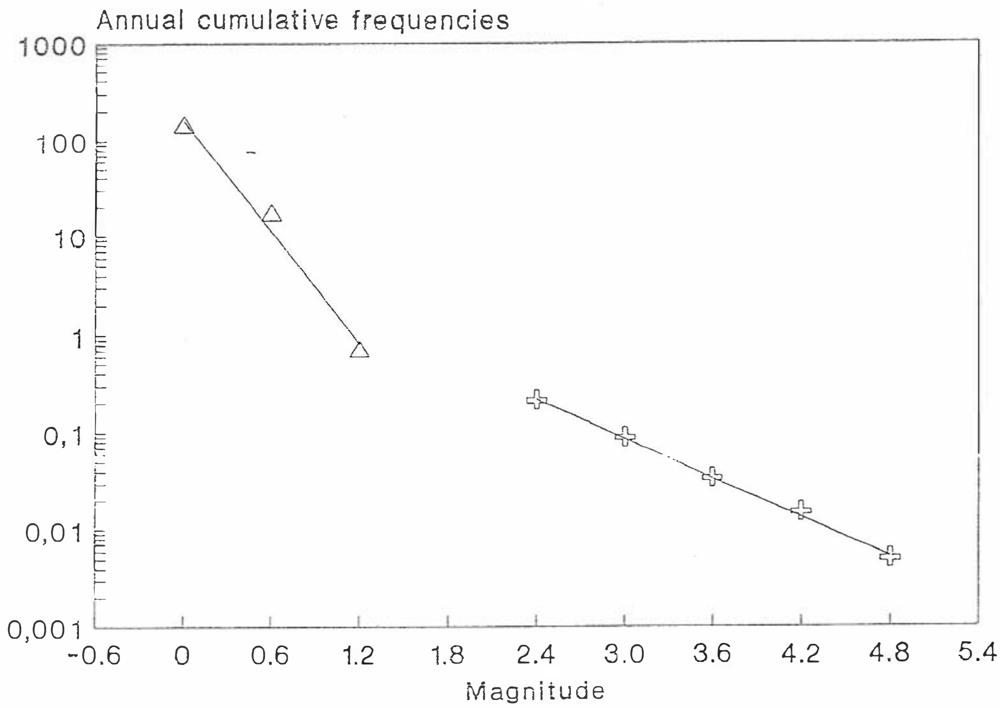

Fig. 4. Cumulative frequencies per year versus magnitude for micro- and macroactivity. Microearthquakes are denoted by triangles, macroearthquakes by crosses. Lines represent least squares solution.

Assuming a stable and consistent long-term tectonic stress release and considering the different time periods it is useful to derive the annual cumulative frequencies for macro- and micro-seismic activity. In correspondence to macroseismic data local magnitudes of microearthquakes are converted according to the relation (3) and summarized in classes with centres M_L:0;0.6;1.2 and the same width of 0.6 units. Half of the width, i.e. 0.3 of a magnitude unit, corresponds to uncertainty in determining M. Distribution of cumulative annual frequencies versus magnitude of both, micro- and macroseismic events, is shown in Fig.4. A quite different behaviour of the magnitude-frequency relation is obvious, discernible by a steeper slope of approximated straight line for microearthquakes. This result remains still valid even though one take into account uncertainty in interpreting the observation period for macroseismicity or a duplication of microearthquake event rate by consideration of ommited daytime events. (The ratio of macroseismic events which occured during the day and at night was approximately 1:1; for this reason the same distribution is assumed for microseismicity). The reliability of the result is mainly evaluated by the conversion of the particular event size (Intensity I for macroseismic and M_L for microseismic observations) into common magnitude scale. An adaption of slope of micro-seismic distribution to that of macroseismic would presuppose a decreasing of proportional factor in relation (3) by 4 times. Comparing with other available relations (TOBYAS, MITTAG 1991) this scatter is outside reality.

4. TECTONIC STRAIN- AND SEISMIC ENERGY RELEASE

The seismic energy E of earthquakes was calculated using the Iida formula

$$\log E = 5.66 + 1.40*M , \qquad (8)$$

the energy being given in joules. This relation was preferred to the frequently accepted Richter relation because it also includes the energy for low magnitudes of microearthquakes.

The long-term macroseismic activity since 1784 was concentrated in two periods at the end of the centuries. For calculations the data set from I=3 upwards can be assumed as quite complete, because lower intensities cannot change the general energy release substantially. The maximum present energy release runs to $6*10^{12}$ J.

With equations (3) and (8) the energy for individual microearthquakes were obtained with the help of local magnitude by formula

$$\log E = 1.18 + 2.03*M_L \quad . \qquad (9)$$

Because of completness only events greater than the above determined threshold magnitude of 2.08 were used . The so calculated seismic energy release within the 20 years period of microseismic observation amounts to a total of $1.8*10^9$ J in night-time and according to the above mentioned assumption $3.6*10^9$ J in the whole time.

The about 100 times higher average annual rate of energy release by macroseismic activity in comparison to microseismic one can be explained by the mainly portion of large events in total amount. The strongest earthquakes with intensities 6.5° released an energy equal to $1.2*10^{12}$ J, i.e. 20 percent of the total energy.

The dependence of the total energy release on the magnitude will be clear by combination of equations (4) and (8) resulting

$$\log(E*N) = 8.93 + 0.73*M \quad . \qquad (10)$$

It means that the larger the magnitude of macroseismic event is, the larger is the total energy released (E*N), in spite of the smaller number of events. However an opposite dependence appears in microseismic observations. According to combination of equation (6) and (9), resulting

$$\log(E*N) = 9.76 - 0.55*M_L \quad , \qquad (11)$$

the total energy release is increasing with lower magnitudes of microshocks, i.e. frequency more contributes to the total amount than the size of the individual events. That means, that the total energy release by microearthquakes would be increased, if additinal events with magnitude below threshold are considered. This remarkable influence is more reflected in relative release of tectonic strain $E^{1/2}$ presented in Fig.5. Comparing the cumulative strain release of macro- and microearthquakes in an equal scale, an equivalent high rate for microactivity as during short activ periods of macroearthquakes is visible.

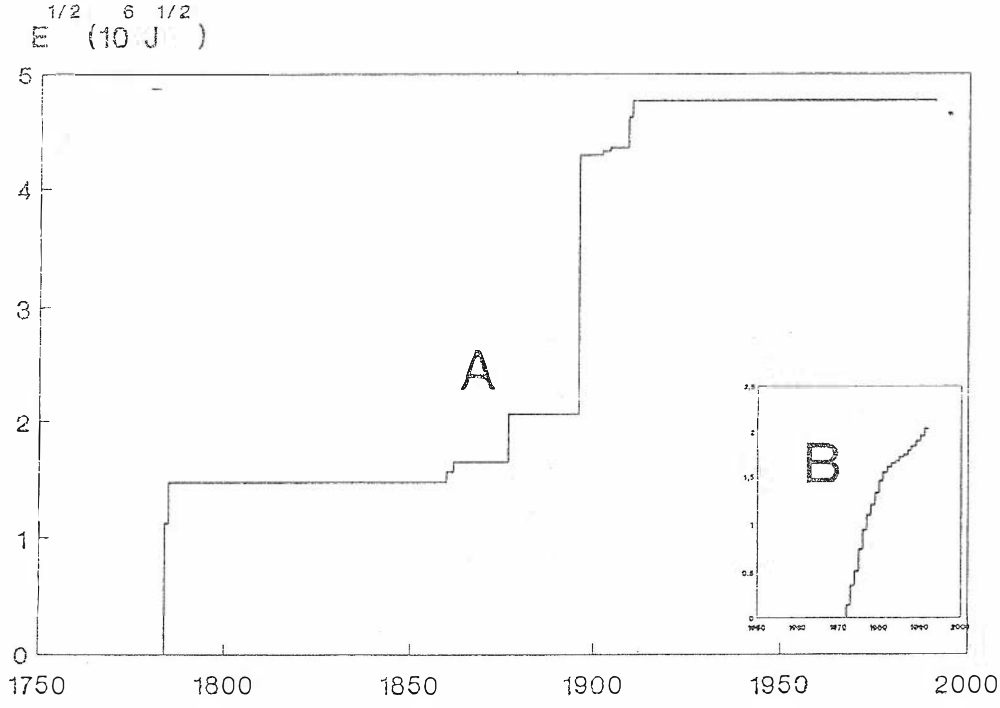

Fig. 5. Cumulative square root of seismic energy release for macroseismic data since 1784 (A) and for microearthquakes observed during 1972-1991 (B).

The detailed course of microseismic energy release together with variations of the b-coefficient of the magnitude-frequency distribution is presented in half-yearly steps in Fig.6. We find that the cumulative energy release may be divided into three phases of different behaviour.

(1) The first phase up to 1974 is characterized by a high rate with nearly constant energy release of $194*10^6$ joule per year and could be a hint to the unknown preceding release.

(2) The second phase enclosing the longest time interval from 1974 to the middle of 1986 exhibit a gradual decreasing behaviour. It begins with a high rate of $130*10^6$ and fall down up to a minimum rate of about $10*10^6$ joule per year. The regular course is interrupted only in the beginning of 1980 by a higher rate similar to the first phase.

(3) Since the middle of 1987 a third phase of an again constant energy release but with a lower rate of $38*10^6$ Joule per year then in the first phase is observed.

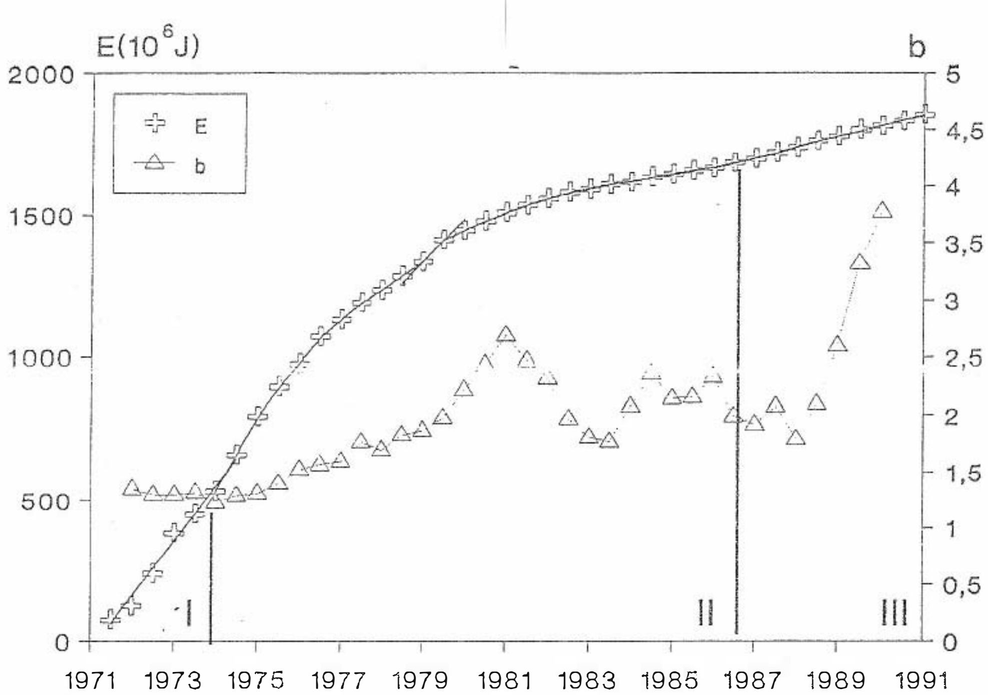

Fig. 6. Cumulative energy release E and b-value variations for microearthquakes observed during 1972 - 1991. Three phases are indicated by the numerals I - III.

The b-value can be estimated immediately by a method of Utsu (UTSU 1966) using formula

$$b = 0.434*n \,/\, (\, M_i - n*M_s) \qquad (12)$$

where n is the total number of earthquakes with magnitude M greater than or equal to M_s and M_i is the sum of the magnitudes M of all the n earthquakes. With the threshold magnitude M_s=0.18 a mean value of b=1.65 for the whole data set was determined. This value is greater than this (0.5-1.5) given usually for earthquake (BATH 1973). Using a correction according UTSU for b-values greater than a given limit a sliding calculation in half-yearly steps with a defined time window over the whole period of 20 years was made. To estimate the minimum length of the time window for significant b-value variation a numerical test was done. It was found that b becomes a stable value for time intervals from about two years. In accordance to this demand b-values were computed for two years intervals and assigned to the interval centre in Fig.6. A somewhat increasing trend of b-value with stronger oscillations in the second half of the observed period is discernible.

5. CONCLUSIONS

Based on observation of weak seismic events within a mining area an attempt was made to connect this microseismicity with the previous stronger macroseismic effects caused by the natural tectonic events within the same region.

Good approximation of both magnitude-cumulative frequency distributions by straight lines with correlation coefficients greater than or equal to 0.994 indicates that the observations are complete.

However, a significant different slope of the mean annual distribution is a hint to another nature of microseismicity. The localised epicentres in the vicinity of the coal mines together with the very shallow focus derived from strong generated Rg-signals (KAFKA 1990) as well as the high b-value may be an evidence for the induced character of the observed microseismicity.

On this understanding first assumption about characteristics of the induced microseismicity in relation to mining activity can be made by interpretation of magnitude-frequency distribution and energy-release in time history.

Both the absence of strong main shocks and a high proportion of small-magnitude events (relatively high b-value) indicates a swarm-like occurence of the sequence (BATH 1978) with the favourable effect that strain energy accumulated due to the mining activity is continuously and gradually released by microtremors.

Comparing the mean return periods deriving from mean annual cumulative frequencies the probability of occurrence of stronger induced events is some orders lower than of natural earthquakes for the same magnitude size. We believe that landslides or rockfalls, expected due to the decreasing of stability of area under investigation in future, may be triggered rather by natural earthquakes than induced events. Besides, magnitudes of the most microearthquakes are lower than of nearby blasts; the strongest recorded blast had a magnitude of M_L=3.3 (i.e. M=1.6).

According to the energy-time development three phases characterized by a stable long term energy release without abruptly changes can be distinguished. The gradual decreasing rate within the main middle phase can not be explained by a linear relation between released energy and logarithmic time as in the case of creep recovery behaviour of aftershock sequences. It appears more probable that a change in seismotectonic regime of the mining volume due to the mining activity is taken as a basis.

The high average amount of 1.65 for b-value refers to an inhomogenous medium with small source dimensions and low strains (KARNIK, PROCHAZKOVA 1976), that means a very suitable seismotectonic pattern for induced seismicity in the region of open-pit browncoal mines. The increasing trend of the b-value corresponds to a decreasing storage of strain energy (BATH 1978). Together with a constant current microseismic strain release similar to that of natural earthquakes in the past a favourable state with regard to seismic risk may be assumed.

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