ACTA MONTANA IRSM AS CR (1998)
Series A No.12 (107), 49–63

MINING TREMOR ACTIVITY IN THE AREA OF THE MINE KLADNO II–MAYRAU AFTER ENDING OF MINING

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ABSTRACT. The mining in the shaft pillar of Kladno II – Mayrau has been terminated on June 30, 1997 and the mine cavities were gradually flooded. The drifting of mine openings, which is the main initiator of the occurrence of mining tremors, has been practically ended already by March 31, 1997. Acoustic and convergence measurements were carried out, at the given location, till the end of extraction. Seismic monitoring from the surface stations is still in due course till the present time. Basing upon these measurements, the decrease of rock–bursting activities and changes in the spatial distribution of foci has been proved and the periodicity of the occurrence of rock bursts in time has been evaluated. The courses of convergence and of seismoacoustics emissions were observed from the viewpoint of a possible prediction of the occurrence of mine tremors.

KEYWORDS: mining tremors, convergence, acoustic emission, rheological deformation.

During the year 1997, an important change took place in the extraction of the shaft pillar of the mine Kladno II – in the mid–year, the mining was suddenly interrupted and ended. This change made itself felt also in the occurrence of induced mining phenomena, by both their number and the released seismic energy. In the indicated area, there was active, in the beginning of 1997, a local seismic network consisting of four 3–component surface and one underground stations (vertical co–ordinate $Z = 201$). In addition to that, during the period from 20.2 through 31.7, the convergence of mine openings and acoustical emissions were recorded at selected sites. Due to the termination of mining, connected with closing of mine workings and gradual flooding of the mine, it was necessary to end also all subsurface measurements. Therefore, only surface seismic stations were used for the purpose of observation of seismic energy releasing due to rheological processes taking place in the rock massif in the given area. The interruption of mining activities in the tremor–prone region is an until now unique case and the analysis of namely seismic data enables the significance of the mining activity and its interaction with natural conditions for the occurrence of rock bursts to be evaluated. An analogous case (in our country) was observed only in the region of ore mines of Příbram, where also the mining activities were terminated and the subsequent seismic observations proved a practically very quick attenuation also of the bursting activity (within a few weeks).

However, in the case of the Příbram ore mines, the occurrence of relatively very strong seismic events (macroseismic effects around degree of 4 MSK64) was observed after an interval of 3–4 years, whose origin was associated with flooding of the mine opening. The ground water level rose from the original 1500 m below surface to 700 m b.s., i.e. to the depth, where the occurrence of mine rock–bursts was observed during the ore extraction. Owing to the water penetrated into the rock massif, contact conditions at the fault structures were subjected to changes and these became seismoactive. Basing upon this experience, it proved significant to observe the seismic activity at the mine Kladno II also during a longer subsequent time period and thus investigate the response of the rock mass to the original mining activity and flooding also in other geological conditions and depths than those in the region of Příbram mines. Results submitted in this paper represent the first stage of this research and their interpretation is also connected with the possibility of evaluation of the deformation course (behaviour) of mine workings and acoustic emissions in connection with the occurrence of mine tremors.

1. Monitored Quantities

1.1. *Technical Mining Parameters*

Among the technical mining parameters, the driving of mine entries and the quantity of mine cars were observed above all. It was already proved by previous studies, that the occurrence of mine tremors is largely connected with drifting of entries as we can see in clustering of foci into the proximity of the drifted mine entries and from the increased occurrence of mine tremors (Rudajev et al. 1972). During the first half of the year 1997, the management of the mining company "Českomoravské doly" decided that the mining will be terminated by June 30, 1997. Owing to this fact, no new driving of entries was carried out and all activities were aimed at the termination of mining in individual sections. The time behaviour of both the drifting and the extraction are evident from Tab. 1. This table illustrates, for synoptical purpose, also the number of seismic stations and the occurrence of tremors.

Tab. 1. Monthly statistics in the year 1997, Kladno II – Mayrau mine

month	1	2	3	4	5	6	7	8	9	10	11	12
number of truck	8786	6794	8412	5065	5799	7652	—	—	—	—	—	—
length of entries [m]	94.1	39.8	41.3	0	17.8	0	—	—	—	—	—	—
underground st.	2	2	1	1	1	1	1	1	1	0	0	0
surface station	4	4	3	3	4	4	4	3	3	3	3	3
number of events	232	190	134	64	75	44	30	18	14	12	15	32
rel. energy $[10^6]$	4.9	4.0	3.6	0.7	1.3	0.5	0.4	0.5	0.3	0.4	0.2	0.7
cumul. amplitude	2070	1369	979	388	530	294	240	173	158	176	143	326

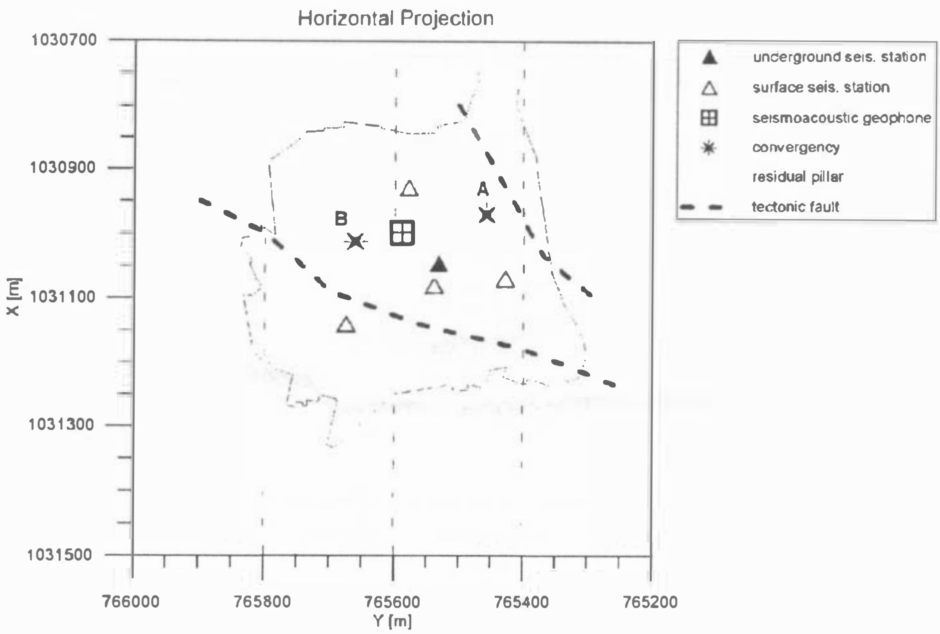

FIG. 1. Schematic map of Kladno II mine situation. Horizontal projection of monitoring method location

1.2. *Seismic Monitoring*

Seismic monitoring by the local seismic network (for location of stations see Fig. 1.) enabled the time series of the occurrence of events, location of foci, and the released seismic energy to be drafted. Location is based on the simplex algorithm, using a homogeneous half–space as a velocity model. Time residuals after location reach around 2 digital samples, which corresponds to a mean location error of up to 30 m. Locale magnitude M is computed from maximum amplitude $A_{\max}$ of the ground velocity and hypocentral distance r: $M = \log(A_{\max}/2\pi) + 0.96\log(r)$, (Fischer and Hampl, 1997). The transformation from magnitude M to energy E was performed on the basis of modified empirical formula (Rudajev, 1985): $\log(E) = 2M + 2$. The location of foci recorded from 1.1.1997 to 30.6.1997 (i.e. during the mining period) is shown in Fig. 2a, b. This drawing contains also locations of mining activities. Positions of foci, created during the second half of the year, are illustrated in the Fig. 3 a, b. Seismic monitoring proved that considerable decrease of the bursting activity took place, but not its entire termination. The course of the cumulative tremor energy and the cumulative number of events is illustrated in Fig. 4a. Fig. 4b. illustrates the course of mining activities – both the length of the drifted entries and the quantity of extracted coal. Since February 1, it is possible to describe generally the course of cumulative energy, by the power series with the exponent lower than 1:

$$Y = 1.79 \cdot 10^6 \cdot X^{0.38}.$$

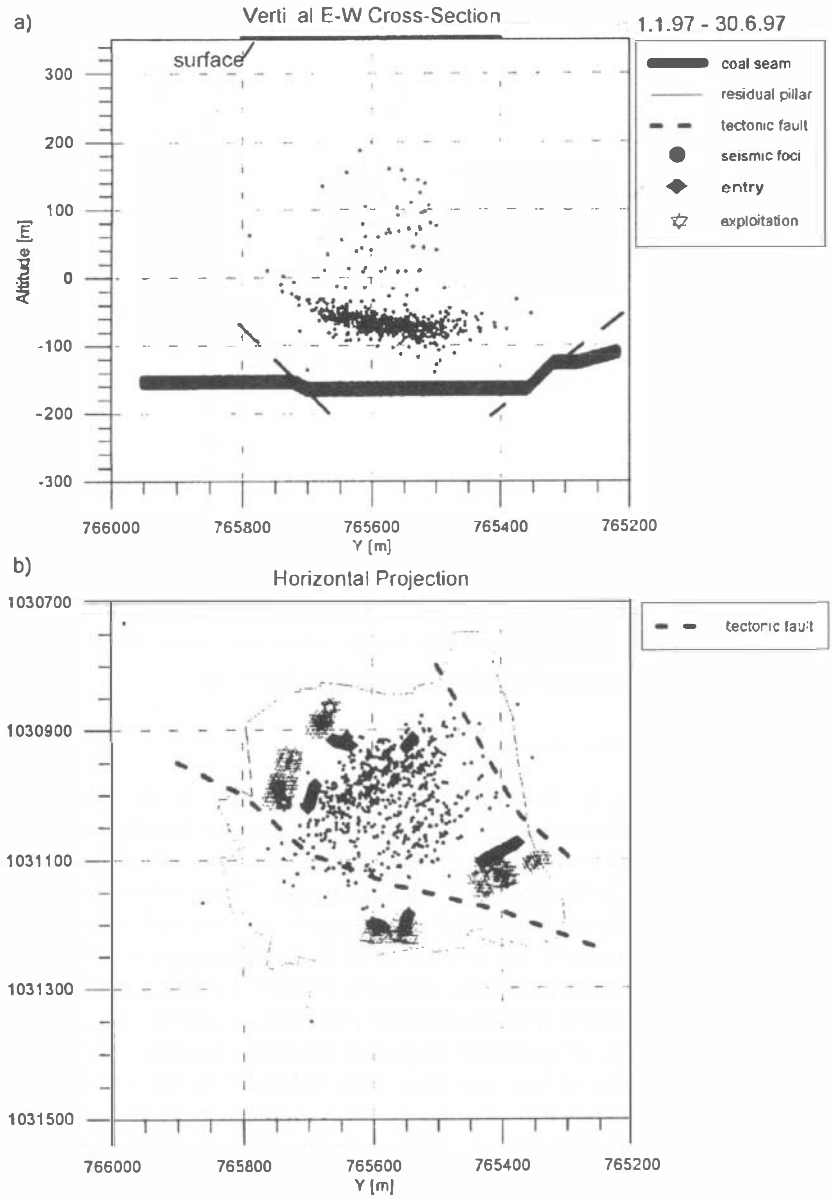

Fig. 2. Schematic map of localized events and mining activities during first half of 1997

This smooth course was disturbed several times by the occurrence of stronger events, see Appendix. It can thus be stated, that a relatively gradual attenuation of the occurrence of seismic events takes place, which is, however, not entirely uniform.

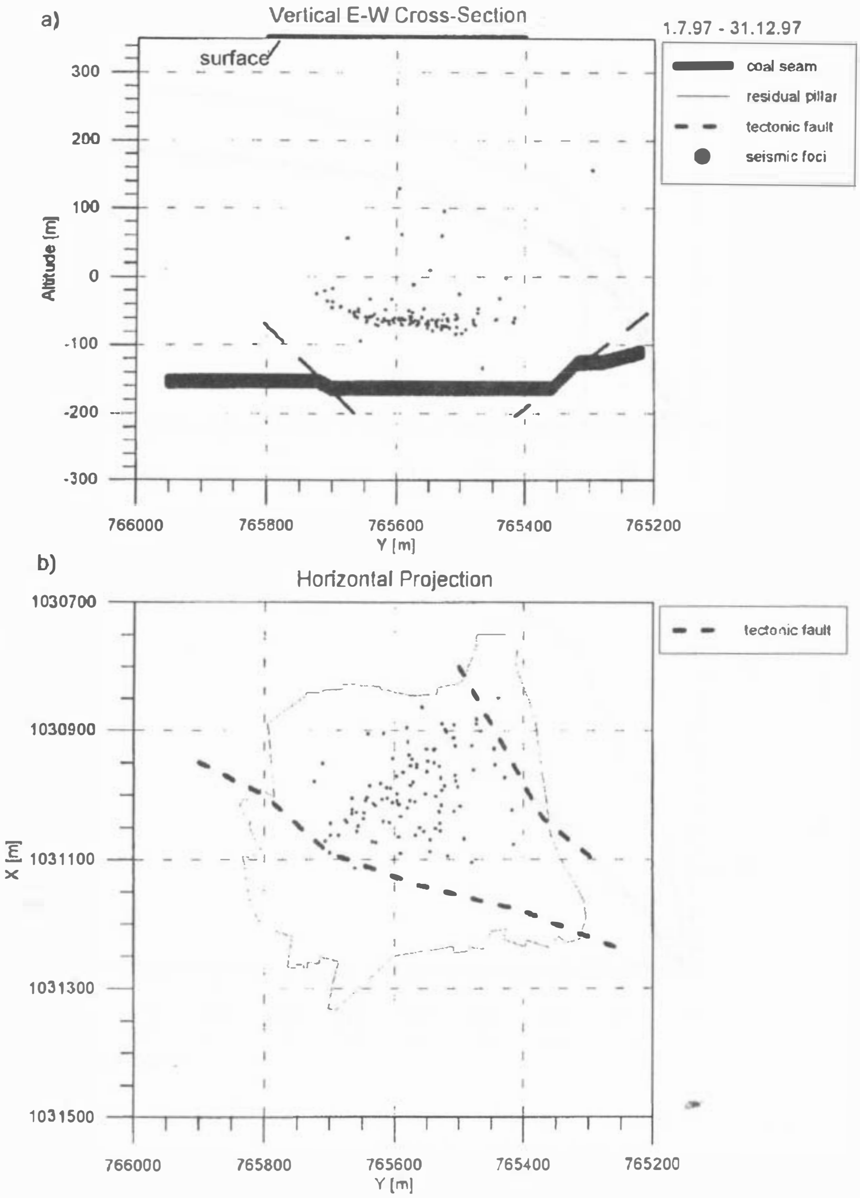

FIG. 3. Schematic maps of localized events during second half of 1997

1.3. *Convergence Method*

Convergence measurements were carried out at two sites marked in Fig. 1. At the site A, both the vertical and the horizontal convergence components of the mine drift were measured. Only the vertical component was measured at site B.

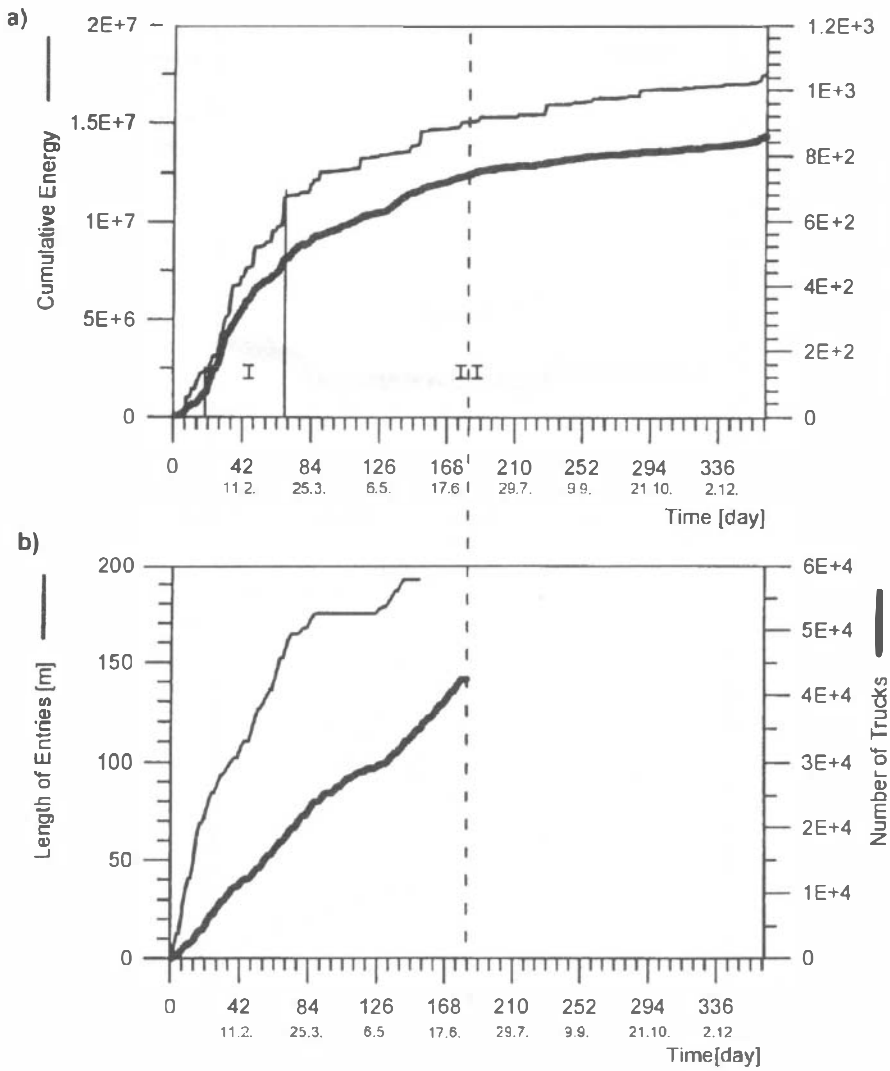

FIG. 4. Cumulative graphs – energy, number of events, length of entries and number of trucks

The convergence was recorded by potentiometric sensors RC13 (Megatron Co.). The record was transmitted by cable with a 1/2-hour recording step. The sensor's sensitivity was 0.01 mm. Convergence measurements were described with more particulars by Živor (Živor, 1998). As far as the possibilities of using the precursory properties of convergence for the prediction of mine tremors, the duration of the recording step enables only the long-term changes of convergence preceding the rock burst to be evaluated. Fig. 5. shows the courses of convergence from 20.2. to 30.7.

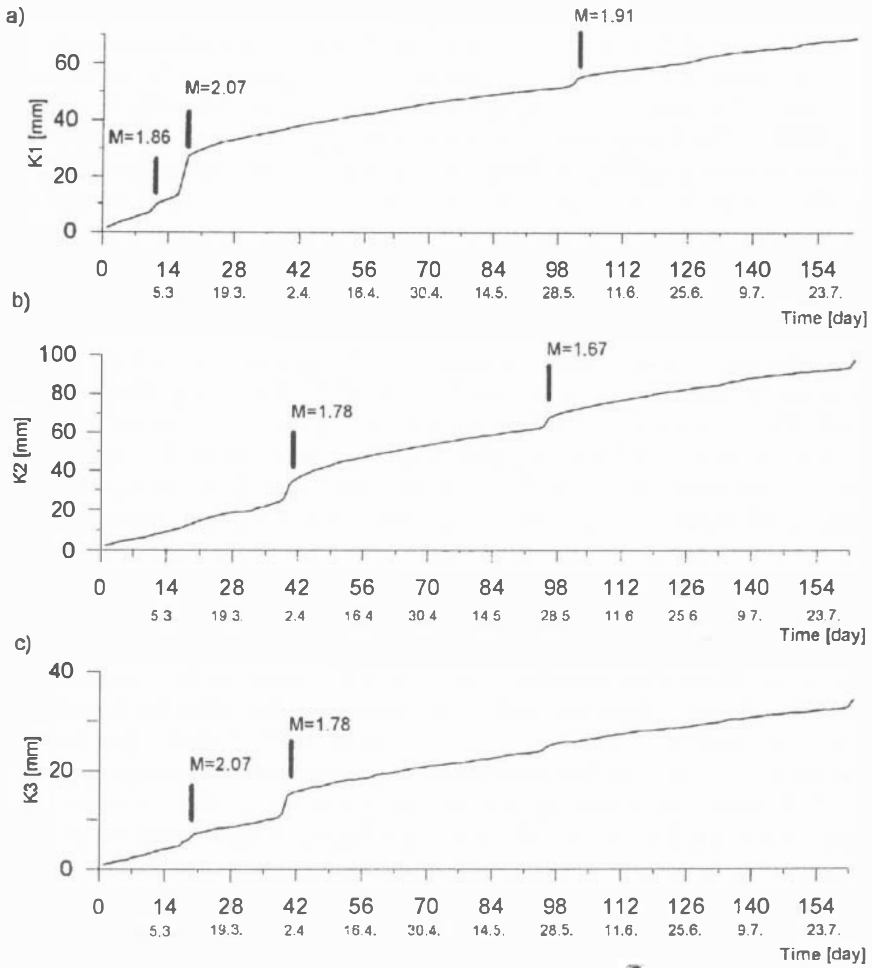

FIG. 5. Convergency time series – measuring point B–K1 (a), point A–K2, K3 (b,c)

Total deformations for the period of 5 months amounted to 35.2 mm (K3 horizontal), 100.1 mm (K2 vertical) at the site A and 64.5 mm (K1 vertical) at the site B. The uniform deformation course is disturbed by a few important changes associated with the occurrence of strong mine tremors. Increased convergence associated with mine bumps is particularly evident during the first 20 days of recording at the vertical component at the site B. The subsequent period shows a linear increase with a single stronger anomaly.

1.4. *Seismoacoustic Measurements*

Within the time period from 20.2. to 31.7., the seismoacoustic emissions were monitored by means of electromagnetic geophone situated in a wall borehole – about 2 m deep – of the mine entry. The monitoring of the seismoacoustic emission enabled only the frequency of seismoacoustic impulses to be evaluated. A more detailed description of the equipment is contained in the study by (Brož and Buben, 1997). The formation of seismoacoustic pulses is very much affected by the mining activities (drilling, colliery car running, blasting works, knocking, etc.). These effects largely exceed the natural acoustic emission, caused by the deformation process in rocks surrounding the mine opening. Examples of anomalies observed during this period are illustrated in Fig. 6a. The comparison of the time anomalies with the course of releasing the seismic energy (Fig. 6b.) reveals the fact that the maxima of the impulse frequency are not connected with the occurrence of stronger seismic events. When investigating the possible precursory properties of the acoustic emission, these anomalies, caused by disturbing effect, should be removed. Their removal is possible, in principle, by several methods, for example by an exact evidence of disturbing effects (namely blasting works) and by reducing the impulse number within the respective time periods or by the analysis of the number of seismoacoustic impulses during the night hours, when the mining activities do not take place. Results of the course of seismoacoustic emission during the night hours and the course of the released seismic energy are illustrated in Figs. 6b, c. The analysis of the frequency course of acoustic impulses and of the releasing course of the seismic energy did not reveal any positive correlation. Such an experience shows that recording of the acoustic emission by a sensor situated within the coal seam, does not enable an interconnection between disturbance of the coal seam and the occurrence of mine tremors to be found. The location of mine tremors revealed the fact that their foci are situated in overlying sandstone layers. It is therefore necessary, for the interpretation of the recorded acoustic emission with regard to the possible time prediction of mine tremors, to monitor this emission in upper holes with sensors located directly in the sandstone layers. Such a location of sensors reduces considerably also the disturbing effects of the mining activities. Reports by (Aksenov et al., 1993; Rudajev et al., 1996) quote analysis results of acoustic impulses, which suggest prediction possibilities of the occurrence of tremors. The study of individual acoustic impulses is based on the frequency analysis of impulses, determining the carrier frequency and the modulated components and, by their evaluation, evaluating the non–linearity trend of the disturbance process. The nonlinearity of processes within the source is connected with the stress increase of the massif and thus with the increasing probability of occurrence of a strong seismic event (Aksenov et al., 1993). The research of a series of acoustic impulses and the evaluation of their randomness of occurrence in time was carried out on the basis of autocorrelation properties of the acoustic emission (Rudajev et al., 1996). Both the autocorrelation coefficients and the course of the autocorrelation functions reveal considerable changes before an approaching total failure. These precursory results were obtained by laboratory model measurements. The above–mentioned recommendation concerning a suitable location of acoustic sensors should be considered a fundamental requirement for a possible application of the discussed methods.

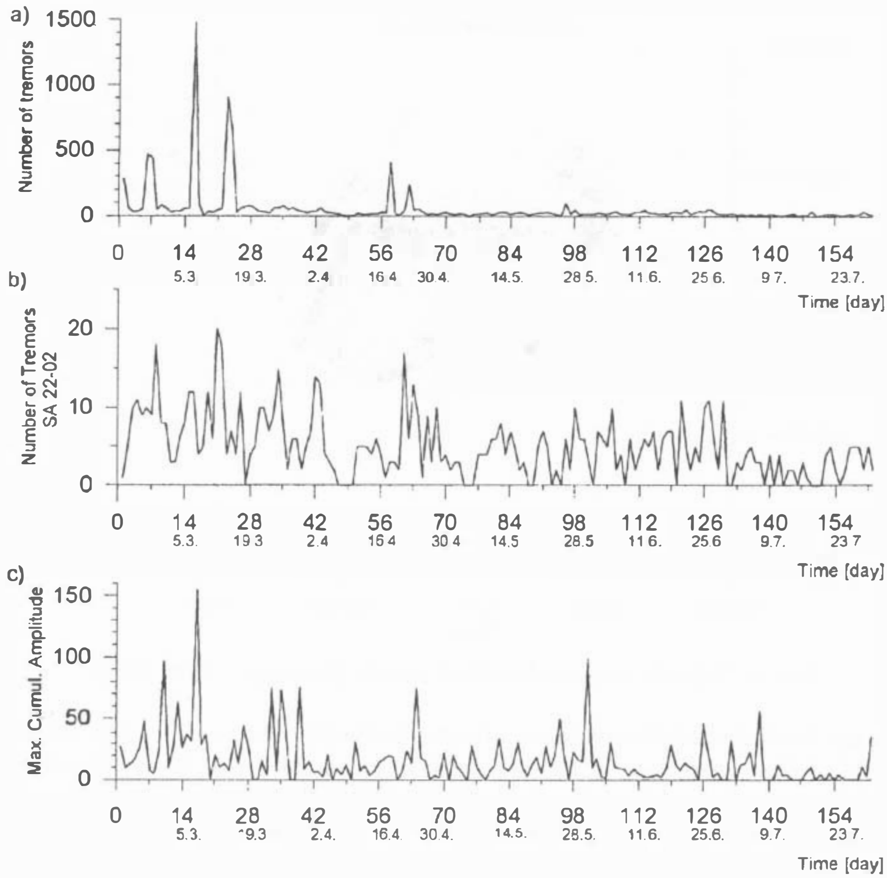

FIG. 6. Seismoacoustic time series (a), seismoacoustic time series selected from 22 to 02 hour (b), seismic time series of cumulative amplitude (c)

2. EVALUATION OF THE MEASURED DATA

2.1. *Spatial Distribution of Mine Tremor Foci*

The seismic monitoring within the mentioned area has been carried out since 1993 by means of the described seismic network. During the time period, when a systematic extraction of the shaft pillar was carried out, it could be proved that the some mine tremor foci accumulate into areas close to the drifted entries. Such an accumulation, for the period from January to April 1994, is shown in Fig. 7. In the year 1997, when the extraction was already restricted, it became evident that the foci are no longer directly connected with entries, their occurrence being concentrated practically to the centre of the shaft pillar. This area is also restricted by two conspicuous tectonic faults, but a connection of these faults with the foci

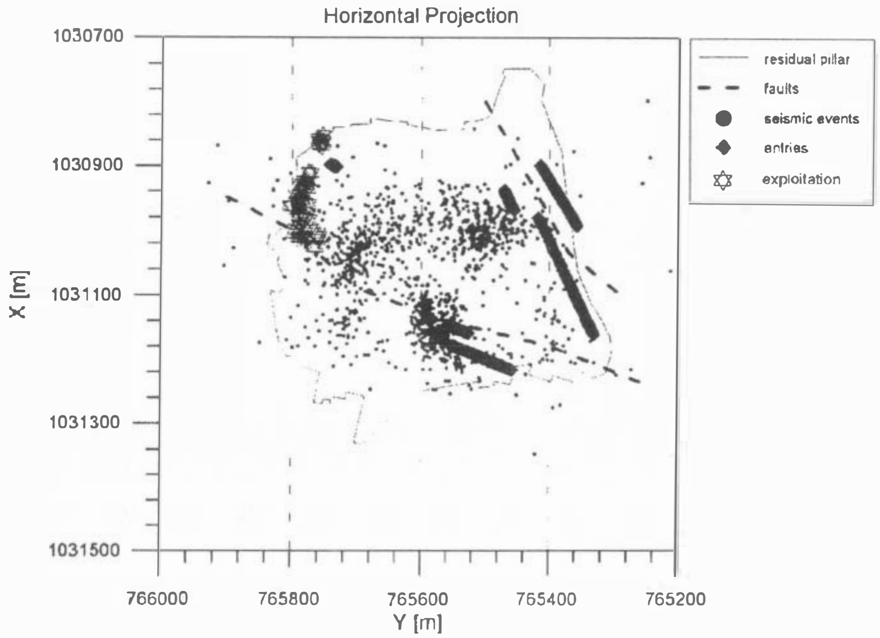

Fig. 7. Seismic maps of localized events (January – April 1994)

could not be observed. Nevertheless, the depth distribution is practically the same as in precedent years, i.e. most foci are located in sandstone layers about 80 m above the extracted seam – Figs 2, 3. During the second half of this year, when the mining has been already terminated, the distribution of foci is practically the same as during the precedent periods, only an important decrease of their frequency being evident.

2.2. *Time Distribution of Mine Tremors*

The releasing course of the seismic energy and the number of seismic events recorded by the local seismic network can be approximated by two linear segments, which do not agree directly with the termination of the mining activity. The first segment (Fig. 4.), when the releasing of the seismic energy is relatively high, being characterized by the line gradient $\mathrm{d}E/\mathrm{d}t = 1.71 \cdot 10^5$ [rel. unit/day] a lasting from 20.1. through 10.3. The final point of this first stage is almost identical with the termination of opening drifting within the shaft pillar. The release of the seismic energy in the second segment, lasting till 31.12., is slower and the linear approximation is characterized by the line gradient $\mathrm{d}E/\mathrm{d}t = 1.89 \cdot 10^4$ [rel. unit/day]. During the first period, the number of 412 tremors was recorded, during the second one 378. The corresponding energy distributions of recorded events are illustrated in Figs 8 a, b. In both cases, this distribution consists of two parts, from the part, which may be characterized by a negatively exponential distribution for tremors with magnitudes exceeding 0.5, and from the descending part for tremors within the interval

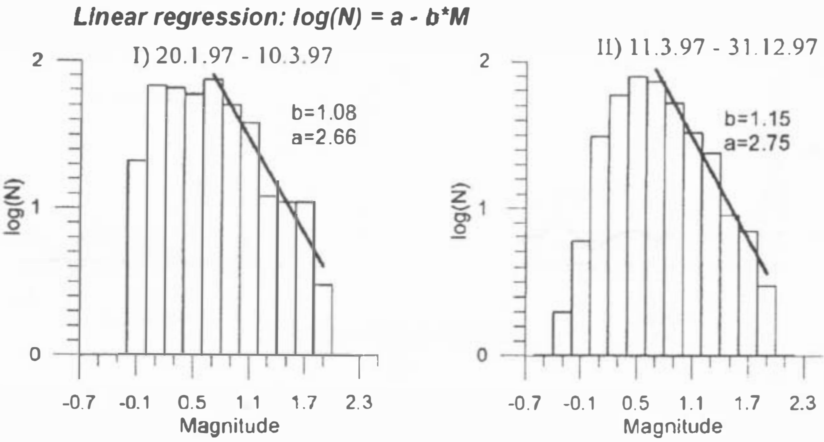

FIG. 8. Magnitude–frequency distribution for time intervals I: 20.1.–10.3. (a) and II: 11.3–31.12. (b)

$\langle -0.1, 0.5 \rangle$. The energy distribution of tremors within the interval $\langle 0.5, 2.2 \rangle$ is thus described by the relation $\log(N) = a - b \cdot M$. In both periods, the characteristic value of magnitude is 0.5 and is evidently connected with the block structure of the overlying rocks (Rudajev et al., 1995). In order to establish the periodicity of the occurrence of mine tremors in time, a correlation analysis of the sequence of tremors was carried out, separately for the mining period – i.e. from 1.1.97 to 30.6.97 and separately for the period, when mining has been already terminated – i.e. from 1.7.97 to 31.12.97. During the first period, a significant 7–days periodicity could be observed, both in the course of the autocorrelation function, and in the course of the power spectrum. The periodicity proved significant both in the sequence of the number of tremors and in the sequence of cumulative amplitudes. This 7–days' periodicity is connected with the operating cycle, because it practically disappeared after termination of mining. Results of analyses are illustrated in Fig. 9., where the thin line corresponds with tremor properties taking place during the mining operations, the thick line corresponding with tremors recorded during the second half of the year 1997.

2.3. *Convergence*

The correlation of the time behaviour of convergence of entries with the course of occurrence of mine tremors suggests the fact that sudden convergence increases are a consequence of stronger mine burst effects. In the case of tremors in Kladno, where foci are associated with the overlying sandstone layers (they do not occur in the coal substance, as it is the fact with pillar coal bumps), the convergence measurements do not exhibit any precursory elements. However, the course of convergence suggests that the deformation of mine openings proceeds linearly also during the period, when the mining activities were already terminated. These deformations are connected with the rheological behaviour of plastic deformations

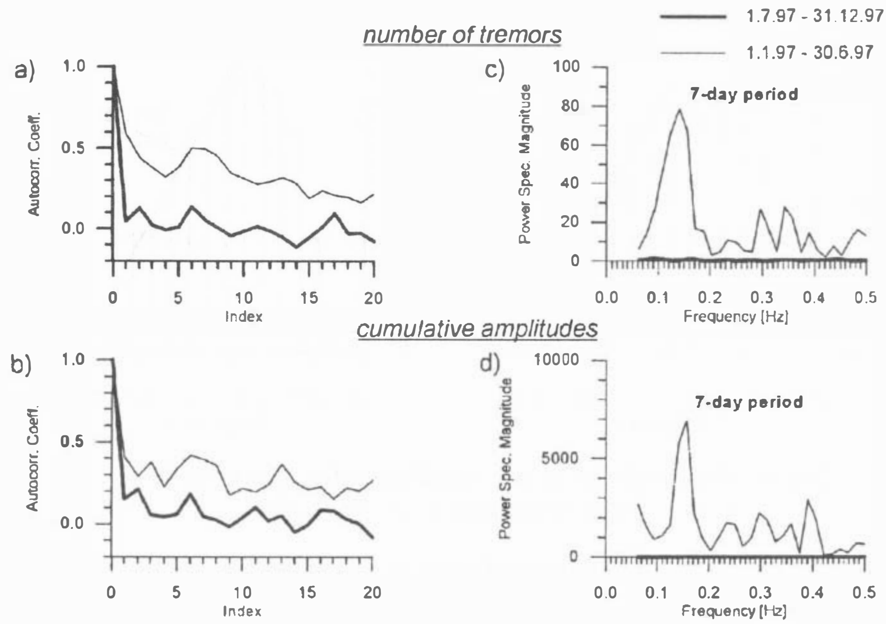

FIG. 9. Correlation function of number of tremors (a) and cumulative amplitude (b) and power spectrum density of number of tremors (c) and cumulative amplitude (d). Thin line depicted time interval during mining activities and thick line after stopping mining

of the rock massif and there weren't any brittle deformations during the release of the seismic energy. The course (since 2.6.97) can be approximated by straight lines of the form:

$$\text{K1:}\ Y = 0.24 \cdot X + 31.25$$
$$\text{K2:}\ Y = 0.36 \cdot X + 37.05$$
$$\text{K3:}\ Y = 0.15 \cdot X + 10.50\,.$$

2.4. *Seismoacoustics*

The acoustic emission senses the brittle failures accompanied with radiation of high-frequency seismic waves. At a near release of the seismic energy in the rock massif a numerous aftershock sequences are created. It was impossible to record a significant drop of seismoacoustic impulses with time. Such a result suggests a considerable effect of the local activities on the occurrence of the acoustic emission and it confirms the fact, at the same time, that the acoustically recorded emission is connected with brittle fractures of the coal seam only. The number of impulses is higher during driving period than after termination of mining. Within the interval from 20.2. to 10.4., the daily average of impulses is 7.1, which correlates with entry drifting about 100 m from the sensor. During the period from 20.4. to 5.5. is the second increase of the impulse number (daily average 5.3) caused by coal mining in the pillar at about 200 m distance from the sensor. The course of the impulse number during the subsequent period from 5.5. to 30.6. has a stationary character, the average value being 4.5 impulses pro day. After termination of mining 30.6.–31.7. is the stationarity maintained, but the average drops to 3.7 impulses. This is connected with deformation in the coal seam only. This result agrees well with the course of convergence of mine openings.

3. Conclusions

Geophysical measurements within the region of the shaft pillar of Kladno II during the mining activities from 1.1.97 to 30.6.97 and during the period after termination of extraction from 1.7.97 to 31.12.97 revealed the following facts:

- the occurrence of mining tremors (rock bursts, mine bumps) continues also after the termination of mining activities, but the frequency of such events decreased. The release of the seismic energy can be described by the linear relation $\sum E = at + q$ with the slope $a = 1.22 \cdot 10^4$ [rel. unit/day]
- the foci of tremors are accumulated into the centre of the shaft pillar and their connection neither with the mining works taking place, nor with the tectonic faults could be proved
- most foci are found in the overlying sandstone bench at the height of about 80 m above the coal seam
- the relation between the mine tremors and the convergence behaviour is significant only for strong tremors – as their consequence. There wasn't found any precursory character for the convergence of mine openings
- the course of convergences is linear during the entire observation period, which witnesses the rheological character of the deformation process of mine drifts
- the seismoacoustic emission sensed directly in the coal seam, does not exhibit, as well, any precursory character. The number of acoustic impulses is very sensible to mining activities. The course of the acoustic emission is stationary by parts, which means that it has a constant average value. This average value is connected with the mining activities and in the last section without any mining works, the acoustic emission is evidently affected by the deformation of the coal seam, as sensed by convergence measurements
- the recorded tremors during the mining operations occur with a significant 7–days' periodicity. After termination of mining, this periodicity disappears and the occurrence of tremors in time appears as accidental.

It may be concluded, basing upon this experience that it is important, for the prediction of mine tremors, to monitor the events directly in the medium, where are their foci. In the given case, the seismoacoustic emission is created in the overlying sandstone layer.

Appendix

Tab. 2. Mining tremors recorded during 1997 with magnitude $M > 1.5$

Date	Time	X	Y	Z	M
8.01.1997	04:40:50	1030957	765554	158	1.90
8.01.1997	14:41:17	1031038	76551	139	1.76
11.01.1997	16:31:14	1030989	765518	97	1.72
14.01.1997	16:44:51	1031018	765558	68	1.60
14.01.1997	19:40:35	1031030	765589	59	1.57
16.01.1997	17:09:19	1031011	765499	76	1.64
22.01.1997	10:58:24	1030942	765535	45	1.51
23.01.1997	10:50:37	1030958	765525	74	1.63
28.01.1997	04:30:11	1030996	765610	104	1.71
28.01.1997	10:30:54	1030954	765543	71	1.60
29.01.1997	04:45:33	1030964	765519	44	1.52
29.01.1997	07:30:29	1030922	765511	107	1.68
31.01.1997	02:45:07	1031033	765560	103	1.71
31.01.1997	17:10:08	1030951	765508	81	1.63
4.02.1997	03:15:02	1030911	765618	188	1.98
5.02.1997	16:53:39	1031013	765676	134	1.79
10.02.1997	17:45:40	1030958	765573	72	1.60
10.02.1997	23:43:34	1030877	765523	95	1.66
13.02.1997	16:51:07	1030952	765538	110	1.74
18.02.1997	03:20:36	1030971	765613	78	1.97
25.02.1997	23:47:23	1030944	765531	63	1.62
1.03.1997	21:23:48	1031015	7655731	61	1.86
4.03.1997	18:30:19	1031006	765559	91	1.65
8.03.1997	12:35:27	1031004	765668	35	2.07
24.03.1997	22:14:32	1031050	765528	144	1.79
26.03.1997	03:32:02	1030964	765571	66	1.65
30.03.1997	18:58:48	1030989	765525	125	1.78
24.04.1997	20:47:25	1030958	765549	145	1.84
25.05.1997	17:55:32	1030991	765516	97	1.67
31.05.1997	09:46:28	1030975	765639	155	1.91
25.06.1997	05:32:45	1031101	765524	72	1.66
31.07.1997	03:54:10	1031026	765530	59	1.54
17.08.1997	06:55:29	1030998	765597	129	1.83
15.09.1997	20:48:18	1031039	765676	56	1.56
14.10.1997	06:49:44	1030991	765526	96	1.72
28.12.1997	18:05:55	1030937	765578	−64	1.66
31.12.1997	20:29:47	1030943	765603	−61	1.56

Acknowledgement. Thisstudy was carried out under the Grant No. 105/96/1065 of the Grant Agency of the Czech Republic.

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