ACTA MONTANA IRSM AS CR (1996)
Series A, No. 10 (102), 39–51

TIME VARIATIONS OF ABSORPTION

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Abstract. A file containing several thousands of seismograms of induced seismic events originating during black coal exploitation in the Mayrau deep mine, Czech Republic, was processed in order to determine the value of absorption. A simple method utilizing the ratio of P and S waves power spectra was tested. The total time period taken into consideration exceeds one year. Significant temporal and spatial variations in absorption were detected. These variations are supposed to be caused by stress changes induced by mining. The mean value of shear waves absorption was determined as $Q_S = 40$. The method is recommended for the purpose of monitoring the state of the rock massif being mined.

Key words: seismic network, induced seismicity, absorption, seismic monitoring

1. Introduction

Absorption is an important factor significantly influencing the spreading of seismic waves. Incorporation of absorption into the interpretation of seismic data or into the solution of theoretical seismological problems is encountered in many cases. Precise computation of energy released in seismic focus is not meaningful without the compensation of maximum observed amplitudes due to unelastic effects, e.g. [Hadzidimitriou et. al. 1993]. Some methods of automatic processing of seismograms utilize reciprocal similarity of data recorded by different stations; restitution algorithms which remove local conditions caused, among others, by absorption, improve significantly the cross–correlation of wave fields. Local structures defined by anomalous absorption may be discovered in prospection seismology; such structures may be further interpreted by means of structural or engineering geology. Some theoretical computations performed for the purpose of engineering seismology show a significant influence of absorption on the response spectra of local structures.

Herein, I describe the method and the results of long–time absorption monitoring in the conditions of the Mayrau deep coal mine (Czech Republic – see Fig. 1). Mining in this mine is followed by the occurrence of a great number of induced seismic events, which generally increase the hazards for the mining activity. Many monitoring methods are applied in the mine with a common goal to develop a prognosis algorithm, which would improve the global safety of mining. The prognosis algorithm will work like a suitable operator with suitable time series on its inputs. All our experience shows that the reliability of prognosis depends also on

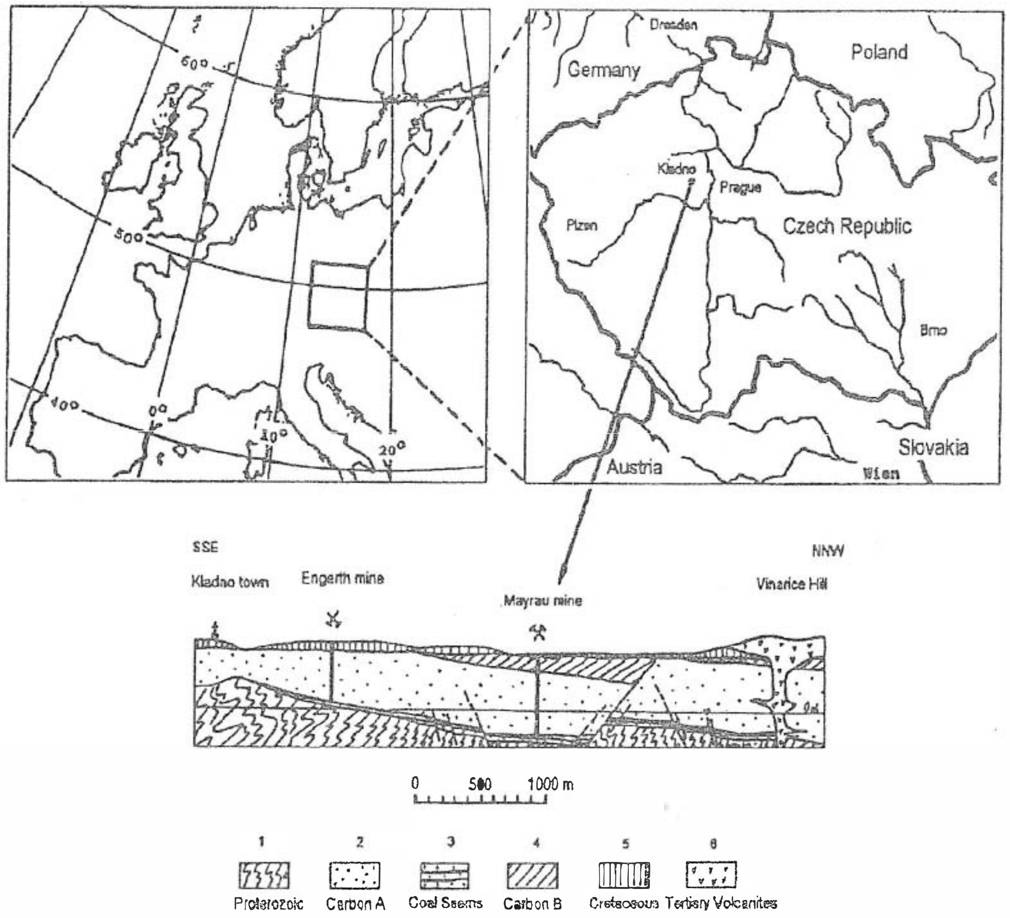


FIG. 1. Schematic map showing the location of the Mayrau Mine also called Kladno 2, the Czech Republic. The seismic network consists of six seismic stations (see also Fig. 2); two underground and the remaining four at the surface. Geologic cross-section after [Živor 1994]: 1 – Upper Proterozoic, 2 – Kladno Formation, 3 – coal seam, 4 – Týnec Formation, 5 – Upper Cretaceous, 6 – Tertiary neovolcanites.

the number of valid input series (channels). One of such input channels may be represented by the current value of absorption in the surrounding massif. The occurrence of induced seismic events is obviously connected with changes in the stress field, and it can be shown that absorption is much more sensitive to the common physical conditions than seismic wave velocities [Clymer, McEvilly 1981; Soloviev 1993]. Some authors have observed temporal variations of coda–Q_c which have been correlated with tectonic activity in regions with natural seismicity [Jin, Aki 1986; 1989; Tsukuda 1988; Sato 1986].

The aim of this article is to recommend a suitable method of the measurement of absorption, to determine the true values and to test potential time variations of absorption. If the search for time dependence of absorption is successful, time anomalies will be interpreted if possible.

2. GLOBAL CIRCUMSTANCES

The Mayrau deep mine is situated within the rockburst–prone area of the Kladno coal basin, about 20 km west of Prague in the Czech Republic (see Fig. 1). The sedimentary basin is built of Carboniferous and Cretaceous sedimentary formations with a total thickness of about 500 m. There is the only exploited seam of black coal lying near the bottom of the basin. Its average thickness is about 7.5 m. The rocks overlying the seam are represented by alternating sandstone, conglomerate, siltstone and claystone beds. The mining area is crossed by two major faults of a general direction NW–SE. Individual blocks are vertically shifted with the displacement magnitude of about 10 m. The safety pillar surrounding the Mayrau mine is the main object of all excavating activity at present. The area of this safety pillar is about 300 × 300 m.

Many induced seismic events occur as a result of mining. The number of events reaches several thousand per year. The strongest events are classified as rockbursts and their magnitude is evaluated as $M = 2$. Many monitoring methods are used in the mine: ultrasonic cross–hole sounding, seismoacoustics, seismology, dilatometry across faults, surface geodesy, monitoring the temperature and conductivity of ground water outflows.

Seismic network is equipped with six stations. Four of them are located at the surface and the remaining two are underground stations. One underground station is located on the 7th floor at a depth of about 400 m, the second one is located on the 10th floor at a depth of about 500 m. The surface stations are three–component, underground ones are vertical only. Registration is performed with a PC in the frequency range of 1 – 50 Hz with the dynamic range corresponding to 12–bit resolution and sampling rate of 250 Hz.

The foci registered in June 1993 – December 1993 are shown in Figs. 2 for the illustration of the seismic activity character. No correspondence can be observed between the locations of foci and the tectonic lines. Most of the foci originate in the overlying sandstone layer, about 80 – 100 m thick, and their locations in horizontal plane correspond to the projections of maximum mining activity. Only a small number of foci lie below the seam. There is a strong time correlation between mining activity and induced seismicity, too. Most events occur in working days (Monday – Friday), while in weekend–days (Saturday – Sunday) one can obtain relative minimum in seismic activity. The opposite relation is valid for mean magnitudes, even though this effect is quite weak. The last statements are documented in Figs. 3 a,b. However, seismic activity is not determined only by the intensity and extent of mining. The number of events per week registered during the year 1993 and their mean magnitudes are shown in Fig. 4. Substantial changes are detected even if the character and intensity of mining remain almost unchanged. Natural circumstances and environment variability cause such departures.

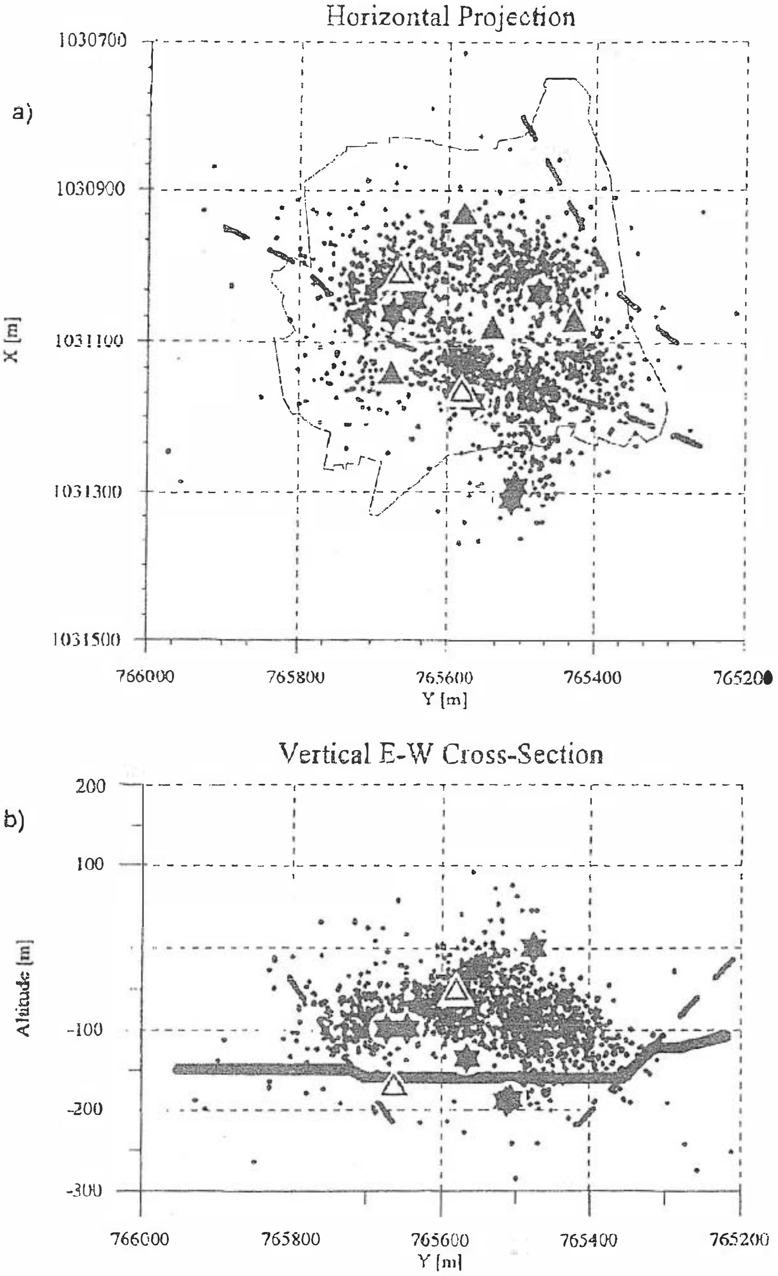
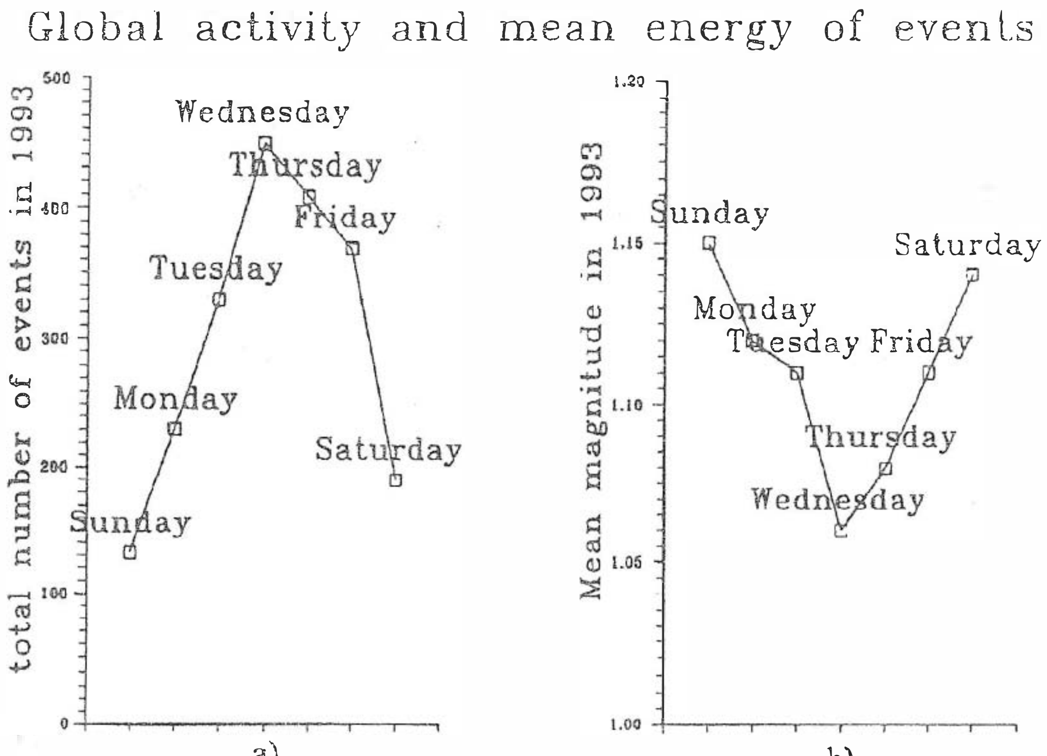


FIG. 2. Maps of localized events during 1994. Local Cartesian system of coordinates is used. The thin closed curve in the upper map is contour of the coal pillar now in excavation. Two thick broken lines are main faults. The thick full line in the bottom part is the coal seam. Altitude of the surface is 352 m. Most foci (d●ts) are clustered in the sandstone layer about 80 m above the seam. Triangles indicate stations (full – surface, open – underground ones). Stars stand for 6 strongest seismic events.



a) b)

FIG. 3. a) Total number of events registered during the year 1993 with respect to the day of the week. On Saturdays and Sundays there is no mining, consequently minimum number of induced events is detected. b) The same for mean magnitude. The magnitude is not corrected for local conditions and has therefore only local meaning.

3. DETERMINATION OF ABSORPTION

Many methods evaluating the absorption are known. The most popular method utilizes the coda amplitude decrease [Aki, Chouet 1975]. This method is used in many modifications for its simplicity, e.g. [Wennenberg 1993]. Interpretation of coda absorption Q_c is rather difficult because both intrinsic attenuation and scattering effects take place. Due to the back-scattering mechanism seems the resulting Q_c to be frequency dependent, e.g. [Rhea 1984; Pulli 1984; Biswas, Aki 1984]. The absorption determined in such way defines globally some part of space surrounding the source and receiver, while the precise limitation of this volume is quite problematic. However, some studies discuss spatial distribution of coda Q_c [Haydar et.al. 1990].

Direct measurement of seismic amplitudes may serve for the determination of absorption in some cases [Nicolas et.al. 1982]. After the compensation for geometrical spreading and possible conversions at boundaries the remaining effect may be explained by absorption. The precision of this method is strongly dependent on

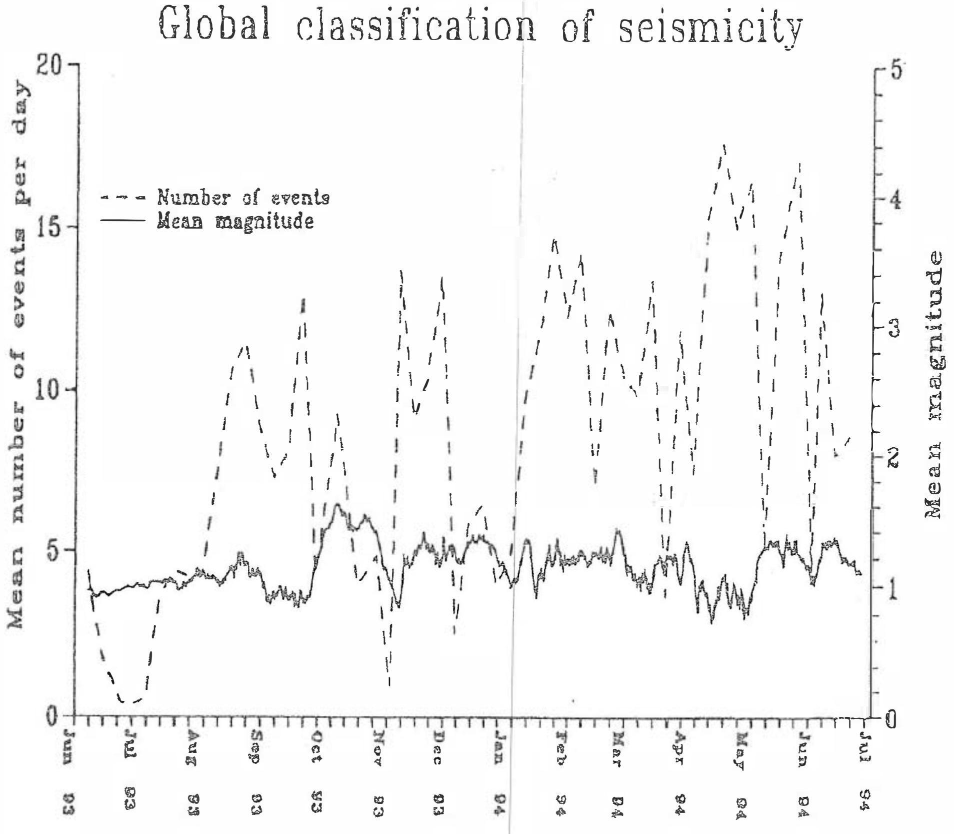


FIG. 4. Number of events exhibits substantial changes, while mean magnitude remains much more stable. Both graphs do not correlate reasonably.

the success reached during the elimination of unwanted effects.

A transfer function between the source and the receiver or between two different receivers may be used for absorption evaluation, too [Rebollar 1984; Hauksson et. al. 1987]. If a direct measurement of the source time function is not available, its shape can be estimated [Růžek, Málek 1992]. When compared with the shape of the registered spectra, absorption can be computed. Broadening of the initial pulse of P wave is known as an input datum for the absorption evaluation in the conditions of shallow engineering seismology [Murphy, Rosenbaum 1989].

The method used in this article utilizes the spectral ratio of P and S waves. This method is similar to the approach of [Clouser, Langston 1991]. It is applicable on records from a single station with identifiable P and S waves.

Let $P_0(\omega)$ and $S_0(\omega)$ be the source power spectra of P and S waves radiated in the direction from the focus to the receiver. The corresponding power spectra $P(\omega)$ and $S(\omega)$ recorded by the seismic station are:

$$P(\omega) = P_0(\omega) \cdot R_P \cdot \exp\left(-\omega t_P / Q_P\right) \tag{1a}$$

$$S(\omega) = S_0(\omega) \cdot R_S \cdot \exp\left(-\omega t_S / Q_S\right) \tag{1b}$$

or, registered spectrum = source spectrum · geometric spreading · absorption where R_P and R_S denote geometrical spreading and conversions at boundaries, t_P and t_S are times of spreading and Q_P and Q_S are quality factors, all expressed both for P and S waves. Without any substantial shortcoming we may suppose a point source and identical rays for P and S waves as well as identical source time function. Under such simplification the following seems to be true:

$$P_0(\omega) = k_1 \cdot S_0(\omega)\,, \qquad R_P = k_2 \cdot R_S \tag{2a,b}$$

The last statements (2a,b) express that both the radiation pattern of the focus and the combination of geometrical spreading plus conversions are frequency independent. P versus S conversions for supercritical angles are frequency dependent in fact but for almost vertical rays and for subhorizontal interfaces, such simplification is quite valid (moreover, homogeneous halfspace was considered in our case). For the ratio of power spectra one can obtain relations

$$K(\omega) = P(\omega)/S(\omega) = k_1 \cdot k_2 \exp\left(-\omega(t_P/Q_P - t_S/Q_S)\right) \tag{3a}$$

$$\log(K(\omega)) = \log(k_1 \cdot k_2) - (t_P/Q_P - t_S/Q_S) \cdot \omega \tag{3b}$$

Let us assume $Q_P/Q_S = 3/4 \cdot \alpha^2/\beta^2$, where $\alpha = 2100\,\mathrm{m/s}$ and $\beta = 1000\,\mathrm{m/s}$ are mean velocities of seismic wave spreading. The last mentioned assumption expresses the fact that no energy loss takes place during pure volume deformation of the medium. The slope of (3b) is $-(t_P/Q_P - t_S/Q_S)$, from which, utilizing only the above mentioned relation between Q_P and Q_S, either Q_P or Q_S can be easily evaluated. Another convenient and simple modification introduces time delay $t_S - t_P$ instead of exact values of times of spreading of P and S waves, so any mislocation and consequent wrong determination of origin time has no effect. Further, an event need not be localized at all. Correct picking of both seismic phases is sufficient. In this text, only Q_S will be further discussed:

$$\frac{1}{Q_S} = \frac{\mathrm{d}\left(\log(K(\omega)\right)}{\mathrm{d}\,\omega} \cdot k/(t_S - t_P) \tag{4}$$

where

$$k = 3 \cdot \frac{(a/b)^3 - (a/b)^2}{3 \cdot (a/b)^3 - 4}$$

3295 local seismic events occurring in June 1993 – July 1994 were used for the computation of absorption following eq.(4). Power spectra were obtained as a sum of all three spatial components N, E, Z. Power spectrum of seismic noise was computed in a window immediately preceding the onset of P wave, too. All spectra were evaluated with the FFT algorithm in the windows of equal length and margins smoothed via cosine functions. The slope $\mathrm{d}\,(\log(K(\omega))/\mathrm{d}\,\omega$ was determined numerically with RMS method, while only such frequency components were taken into consideration, where both P– and S–wave power spectra exceeded at least three times the corresponding level of noise.

Only two surface stations BYT and KRY were used for the analysis. This restriction has two reasons. First, it is only at surface stations that P and S waves can

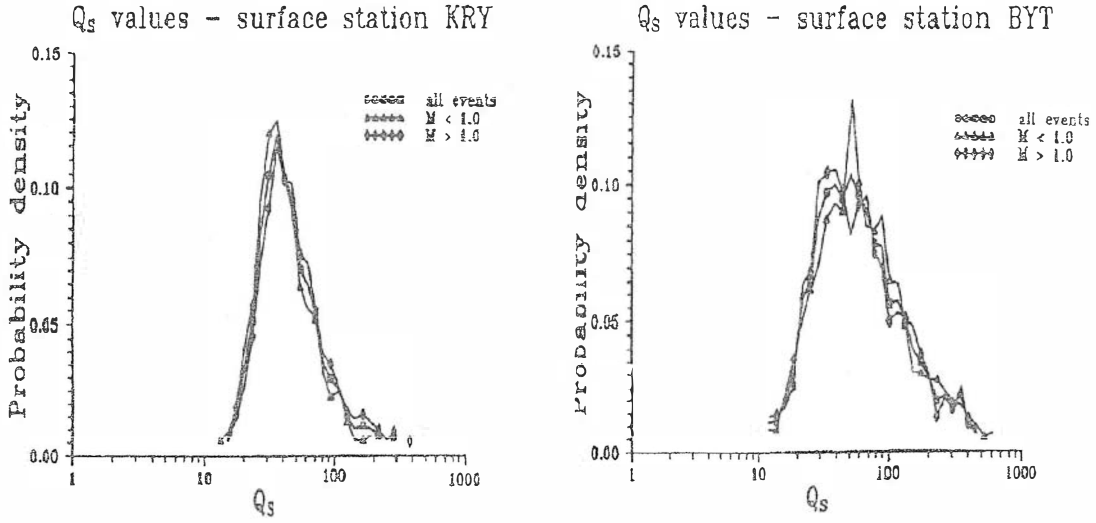


FIG. 5. Histograms of Q_S obtained from stations KRY and BYT

be reliably distinguished from each other. This distinguishing is due to sufficient hypocentral distances and favorable character of polarization. On the other hand, underground seismic stations produce too complex seismograms. Secondly, only stations BYT and KRY were in operation during the whole time of investigation without any dropout, thus warranting perfect homogeneity of input data. Simple statistics of the resulting Q_S values is illustrated in Figs. 5 a,b. Probability densities for both stations and for three cases are given there: all seismic events, only "weak" events and only "strong" events taken into consideration. As the mean magnitude is very close to $M = 1$, this is the magnitude level used for the discrimination between "weak" and "strong" events. No meaningful difference between "weak" events absorption and "strong" events absorption is observed, which is in good agreement with our expectation. Mean values for both stations are about $Q_S = 40$. The corresponding P–wave absorption would be approximately $Q_P = 240$. The shapes of all graphs imply logarithmic Poisson distribution but no further analyses were performed in this direction.

4. TIME DEPENDENCE OF ABSORPTION

Some smoothing of data must be performed in order to obtain reasonable time dependence of absorption. Logarithmic averaging in sliding time window of variable width was used. The current width of this window was chosen so that a constant number of data points was present inside any time.

The resulting graphs for the two surface stations are given in Fig. 6. Interesting features can be seen in this figure. All available data are taken into account now. Q_S from the two stations differ significantly (even by more than 100 %) in the time period of June 93 – January 94, while both graphs are nearly identical later. Such discovery implies both temporal and spatial variability of absorption. There are three remarkable positive anomalies detected by station BYT between

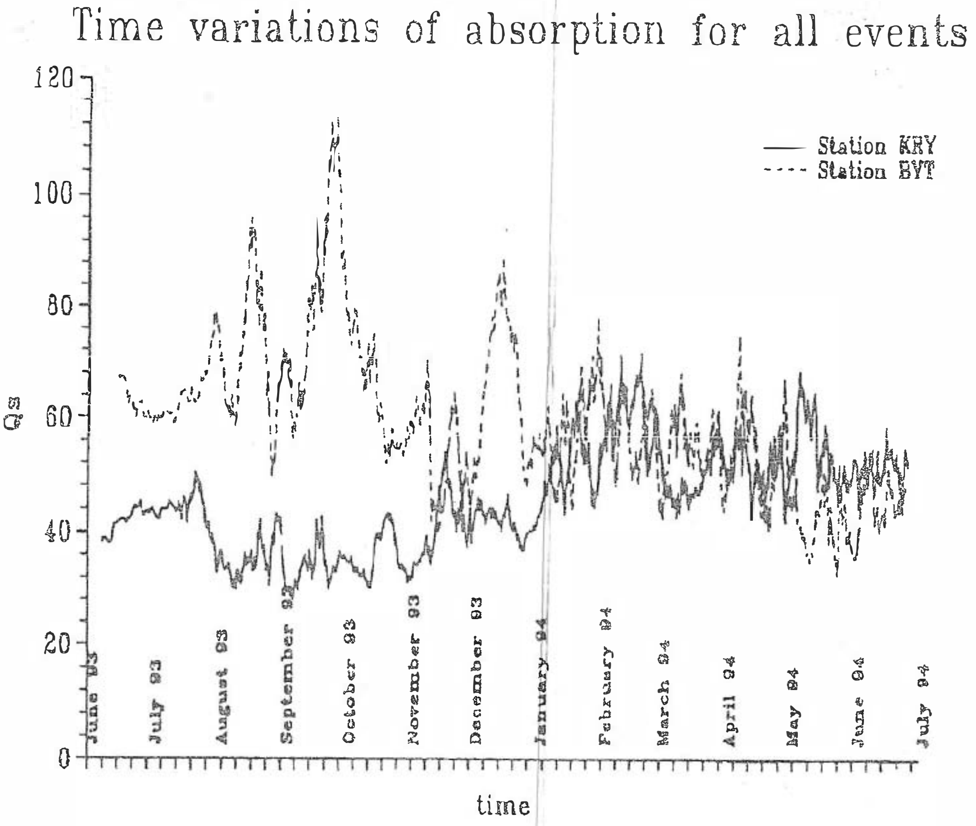


FIG. 6. Smoothed graphs of Q_S for both discussed stations. Time labels correspond to the beginning of each month.

the last quarter of July and the beginning of October 1993. The highest value of Q_S reaches 110 at the end of September. No correspondence with station KRY is visible. Another similar positive anomaly ($Q_S = 85$) occurred at station BYT during December, also having no parallel at station KRY.

The explanation of such different, and maybe suspicious, dependences seems to be topical now. There are several reasons considered.

a) Seasonal (external) sources of variations. It is well known that the increase in soil humidity results in better conditions for seismic wave spreading. Unfortunately, a deeper analysis of precipitation variation did not show any correlation with positive Q_S anomalies. Moreover, both stations BYT and KRY are situated at the surface close to each other, and it is not probable that increasing precipitation would influence selectively only one station. Further, rays connecting the foci with the stations are nearly vertical, and only a small part of them (cca 1 %of their length) intersects the surface layer, in which the water content may vary, so the potential effect would be very weak if any. Finally, one can exclude seasonal sources from the responsibility for the observed absorption variations. The same conclusion may be drawn for freezing of the surface layer of soil, and, moreover, such mechanism is quite irrelevant during autumn months when Q_S changes occurred.

b) Focus changes. It was shown experimentally that the computed values of Q_S do not depend on the magnitude of events (see Figs. 5 a,b). The properties of the source are fully excluded from computations due to the use of the ratio of P– and S–waves spectra in eq.(3). In order to do this, it was necessary to make some simplifications of the seismic source, while it represents a rather complex phenomenon in fact. A short study was therefore devoted to the focal mechanism of induced events. An ensemble containing 12 randomly selected events was processed with respect to the determination of common focal characteristics. It was found [Šílený 1994 – personal communication] that the focal mechanism of all investigated events is very similar and thus no variations in source properties were indicated. Induced events are globally characterized by a combination of shear and implosion mechanism, while the implosion contributes substantially. Hence, the focal mechanism does not seem to generate the observed absorption variations either.

The method used for the computation of absorption compensates the hypocenter distance via the $t_S - t_P$ time delay (eq.4). Clustering of foci and time migration of such clusters may be also considered a source of false absorption variations due to the neglecting of complex 3D geologic structure. Such mechanism of generation of absorption anomalies can be fully excluded, too. Mean depth of foci remains the same during the whole period taken into investigation. Even though the horizontal positions of epicenters show a weak linear trend in the direction to the south (sure due to the advance of mining), the magnitude of such movement is only a few meters per year.

Finally, no effects connected with the focus seem to be able to explain the observed time or space variations of Q_S.

c) Changes in the medium. Temporal changes of the transfer function between the focus and a seismic station can be considered the most probable and quite natural explanation of the detected time functions describing absorption. Strong seismic events and/or mining activity itself are connected with local redistributions of stress. These stress changes result either in widening or in closing of cracks present in the massif, possibly in generating of new cracks and dislocations. Such process may cause both temporal and spatial changes in transfer function. Due to the local character of stress changes, rays connecting the focus with station BYT are influenced differently from the rays connecting station KRY. Both rays differ sufficiently because the average angle at which they intersect in the focus is about 30 degrees. In such way different shapes of both curves in Fig. 6 can be explained: Stress, and consequently transfer function changes occurred only in those parts of the massif which were mapped by the rays towards station BYT.

Correlation of Q_S with the number or mean magnitude of events (Fig. 4) gives an equivocal explanation. A deeper analysis of mine documentation showed that the worst conditions for mining occurred after September 1 and after December 1. In both cases strong seismic events occurred ($M = 2.1$ and $M = 2.5$). This is not so exceptional from the global point of view but some destruction of galleries took place in the mine and necessary restrictions of mining activities were introduced then. If such events are of prognostic interest, absorption itself seems to be rather a seismic postcursor than seismic precursor.

Correlation analysis between coda Q_c and b–value is suggested by [Jin, Aki 1989] in the case of natural earthquakes. This approach is impractical in our case because of the small range of the observed magnitudes (0.5–2.5) precluding any comparison up to now.

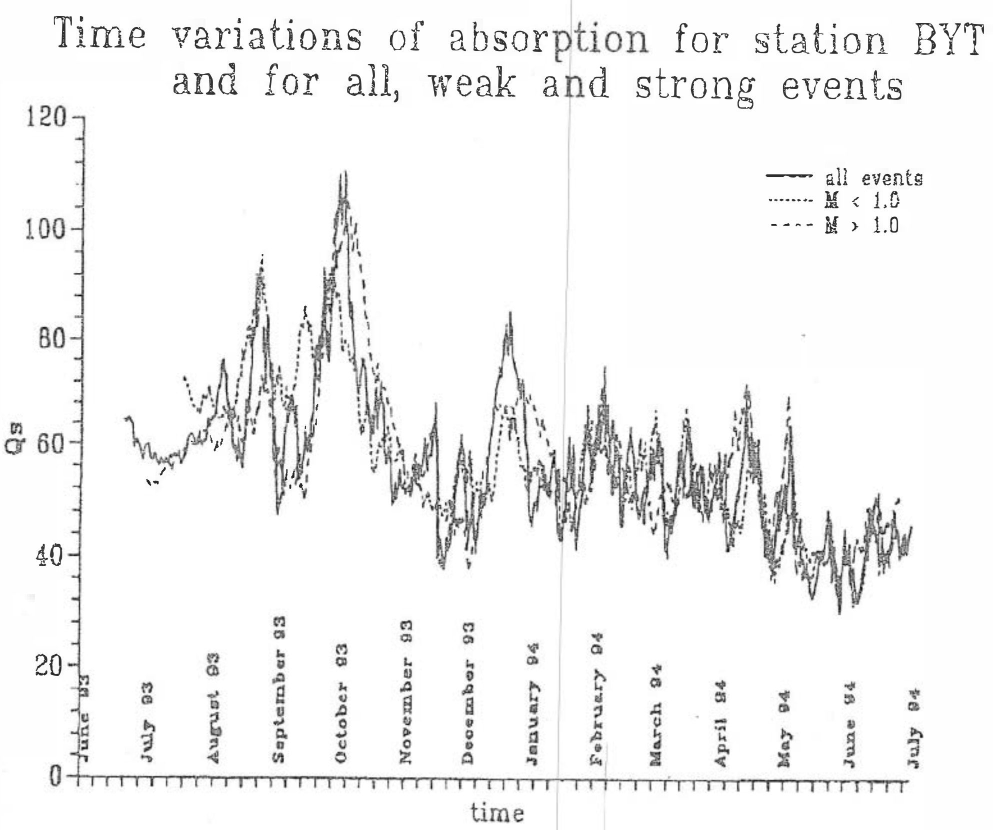


FIG. 7. Q_S obtained separately for "strong" and "weak" registered with the station BYT. Note the similarity of all three curves.

Time series representing absorption classified selectively into "weak" and "strong" events are shown in Fig. 7. Both "weak" and "strong" events give nearly the same curves, which is quite acceptable. The critical value for the discrimination between "weak" and "strong" events is the magnitude level $M = 1$. Small discrepancies between all curves in Fig. 7 may be explained by the same mechanism as that responsible for the differences between the two curves in Fig. 6: spatial distributions of "weak" and "strong" events are slightly different. Similar analysis of time series for "weak" and "strong" events recorded by station KRY produced graphs yet closer to each other.

In order to test the influence of the seismic focus position on the absorption value, source area was divided into four rectangular sectors A1 – B2. This division is quite arbitrary and has no physical meaning. Only data associated with the foci localized to a particular sector were used. Because of the low number of events originated

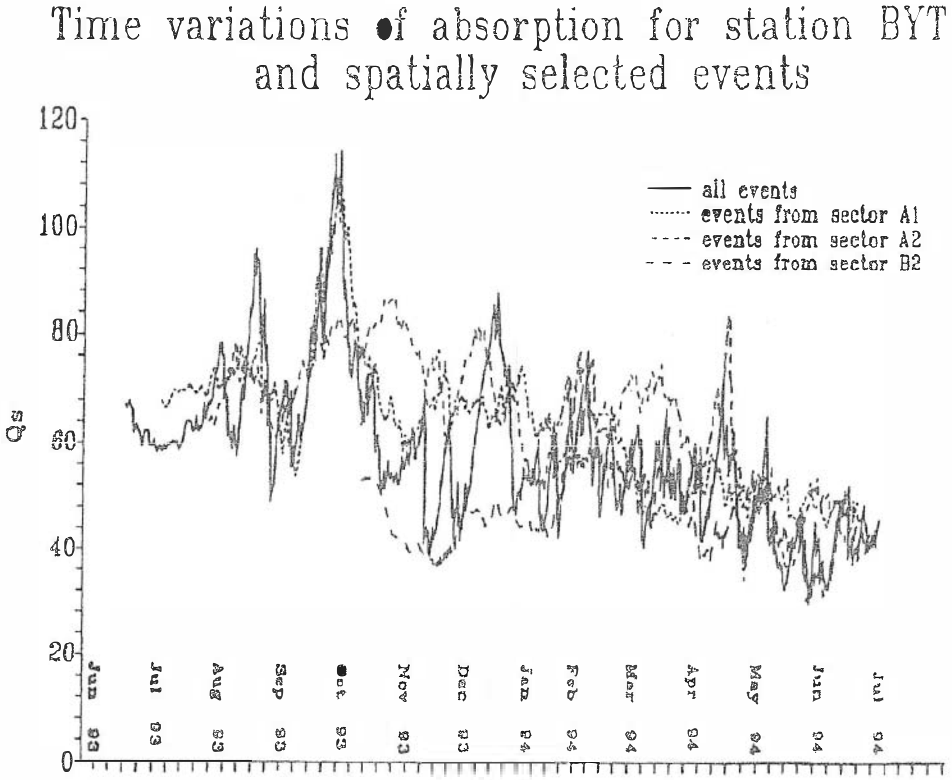


FIG. 8. Q_S from different source areas A1, A2, B2 (for sectors see also Fig. 2) for station BYT. Note the difference of all graphs indicating the spatial inhomogeneity of the transfer function.

in sector B1 only the remaining three sectors are presented graphically in Fig. 8. Much higher variance of curves is obtained in comparison with the graphs from Fig. 7, indicating a stronger dependence of the computed absorption on the focus position. This fact may be advantageous in some cases because the computation method used above gives results which are connected with certain rays. As a result, the absorption values can be potentially attributed to clearly defined volume.

5. CONCLUSIONS

The method of absorption determination from the ratio of P– and S–wave spectra seems to be quite stable, simple and suitable for the purpose of continual monitoring of the state of the rock massif. The obtained results are realistic and exhibit both spatial and temporal variability. Due to the complexity of mining processes it is impossible to define a straight deterministic dependence between the current values of absorption and some other attributes of mining. Instead, a more sophisticated approach is recommended to be further developed. First, the presented method provides results which are directly bound to distinct rays, unlike the well–known coda–Q_c measurements. This fact has to be utilized, and the values of absorption should be differentially determined for separate parts of the massif by means of suitable tomographic method. Secondly, some statistics integrating both geophysical and non–geophysical methods has to be incorporated in order to increase the reliability of results. The obtained spatially–selected time series should be studied together with other attributes of mining. Generally, monitoring of absorption seems to be promising in connection with the development of an algorithm solving the seismic activity prognosis.

Acknowledgement: This paper was particularly funded by the Grant Agency of the Czech Republic, registration number of the project 105/96/1065.

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