of the bed and the shape of the caving zone confirm the possibility of tensile stresses arising in the stope chamber roofs and the danger of level pillar breakage at the boundary with the collapse zone. We have recommended to the mine management using a compliant support pillar of the first type as the level pillar in order to increase the angle ψ of the pillar reaction and thus attain a compression of the stope chamber roof perimeter and prevent pillar breakage. According to estimates, the pillar will increase the ore reserve in stope chambers by 20% at Severnaya Mine, cutting down operation losses and ore deconcentration.

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"SOFT" SEISMIC EMISSION IN THE "TASHTAGOL'SKAYA" MINE

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Seismic observations conducted in shock-prone mines indicate that soft ground motions, whose vibration spectrum is limited by infrasonic frequencies, occur together with sudden seismic jolts, which damage mine excavations and which are accompanied by sonic effect. In some cases, the recorded shape of these vibrations is reminiscent of a volcanic tremor that precedes eruptions [1]. The application of the term "mine tremor" to the seismic emission caused by exploitation of the deep-level mines in South Africa is most likely associated with this [2].

In seismic emissions associated with the exploitation of the "Tashtagol'skaya" mine, sharp jolts alternate with wave trains in the infrasonic region. During observations in the near-source zone — at distances not exceeding 33 km from the wave source, separation of any type of emission has become possible on the basis of spectral signatures. In this case, the term "soft" emission, which is borrowed from seismology, where "soft" or "slow" earthquakes are categorized [3], is used for signlas, whose spectrum does not extend beyond the limits of the infrasonic region (0–20 Hz). The term "rigid" emission is used for shock-type emission, whose spectrum extends beyond the limits of the infrasonic region.

The purpose of investigating the seismic emission in the "Tashtagol'skaya" mine was to gather data for the development of a scientific base for predicting powerful mine shocks. In our study, we present the initial stage of this investigation, which included as a task, the derivation of basic characteristics of "soft" emission in selecting a theoretical model that would describe it.

APPARATUS AND METHOD OF OBSERVATIONS

The observations were conducted using the portable earthquake-recording apparatus "Region" [4], which makes it possible to record continuously the velocity of ground motions in the 1-30-Hz frequency range with a 40-dB dynamic range. Seismic signals transformed by VÉGIK-

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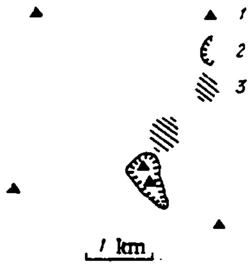

Fig. 1. Schematic diagram of observations: 1) observation points; 2) boundary of ore body being excavated; 3) region of generation of "soft" seismic emmission.

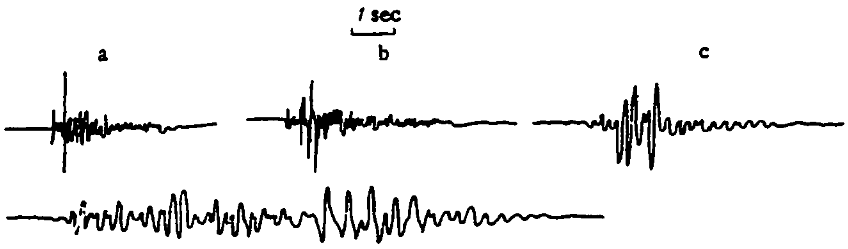

Fig. 2. Recordings of various seismic disturbances at point situated on surface at epicentral distances of 1.5–2.5 km: a) mine shock with energy of approximately 10^6J; b) blast produced from 3.5 tons of explosives; c) "soft" seismic emission of different duration.

type sensors were amplified and recorded on magnetic tape. The recordings obtained were reproduced in visible form in two receivers. All data obtained were first output in compressed form on photographic paper using a light-beam oscillogrpah; selected segments of the recording, which were identical to useful signals, were again reproduced on the oscillograph at an increased scan rate. In addition to producing oscillograms of the seismic signals, their frequency analysis was also made possible using a similar apparatus consisting of a set of narrow-band filters, whose tuning frequencies cover the range of the frequencies measured. The frequency analyzer employed made it possible to obtain seismic-signal spectra consisting of 11 readings where the bandpass of each filter was 0.5 octaves.

A three-component recording of seismic signals generated in the mass near the mine was carried out simultaneously at five points, three of which were located on the surface at distances of from 1 to 3 km from the mine, and two inside the mine at a depth of approximately 800 m from the surface (Fig. 1). This arrangement of instruments corresponded to a network of stationary observations, which was planned to permit representative recording of all seismic signals emitted from the space near the mine, beginning with an emission energy of 10^4 J.

RESULTS OF OBSERVATIONS

Continuous recording of vibrations from July 20 through September 12, 1983 made it possible to record, in addition to blasts, 123 seismic signals, whose sources were located in the vicinity of the mine. Of these, only three signals could be attributed to the "rigid" type of emission (seismic jolts). The oscillograms of these signals contain distinct appearances of longitudinal and transverse waves, and are similar in general pattern to recordings of production blasts produced from charges containing 1-5 tons of explosives (Fig. 2a and b). Two of the three recorded jolts appeared as mine shocks of moderate force. The remaining 120 seismic signals are attributed to a "soft" type of emission. Their recordings are with respect to the low-frequency vibrations, whose duration varies from 3 to 20 sec (see Fig. 2c). The "soft"-emission signals originated relatively uniformly with time.

The results of spectral analysis of some of the recorded seismic signals are presented in Fig. 3. The "Rigid"-emission spectrum obtained for a signal recorded at a distance of 0.7

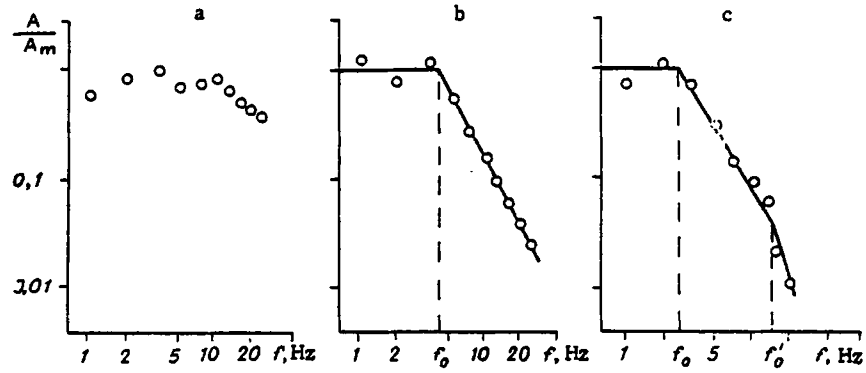

Fig. 3. Spectra of displacement amplitudes of "rigid" and "soft" seismic emission: a) mine shock recorded at point on surface at epicentral distance of 1.5 km; b) "soft: emission recorded at internal point within limits of region of generation; c) "soft" emission recorded at point on surface at epicentral distance of 1.7 km.

km from the source (Fig. 3a) is characterized by a relatively uniform amplitude distribution over the range of measurements. The presence of horizontal and descending branches, which can be approximated by segments of a straight line when constructed in a log-log scale, is characteristic of "soft"-emission spectra (see Fig. 3b and c). These spectra are described by the introduction of two parameters: the angular frequency f_0, which defines the position of the spectrum's point of inflection, and the slope factor of the descending branch

$$\alpha = -\lg A/\lg f,$$

where A is the spectral amplitude, and f is the frequency.

The "soft"-emission spectra were plotted for two observation points. The first of these points was located inside the mine at a depth of approximately 0.8 km, and the second on the surface at a distance of 1.5 km from the mine. It was assumed that the first point lies within the emission zone, and the second outside this zone at a distance commensurate with the dimensions of the emission zone. The spectrums corresponding to these points (shown in Fig. 3b and c) were obtained by averaging data derived from the processing of 10 signals with approximately the same duration. The results of analysis indicate a significant difference in the spectrum of signals recorded at various distances from the source of emission. In the first case, the break in the spectral curve occurs at a frequency of 4.5 Hz, after which the spectral displacement amplitude decreased in proportion to the square of the frequency ($\alpha = 2$): in the second case, the break in the spectral curve occurs at a frequency of 3 Hz and a second break is projected at a frequency of 16 Hz at which the slope factor of the descending branch changes from 1.6 to 3.1.

The energy of the "soft"-emission signals was determined in the following sequence from data of the spectral analysis. The density of the energy flux through the surface of a sphere with a radius R was first determined for each of the signals recorded at three observation points located on the surface; for this purpose, we used an equation derived for the applicable type of frequency analyzer [5]:

$$\varepsilon(R) = \frac{1}{2}\rho v \sum_{k=1}^{n-1} (\Phi_{k+1}^2 + \Phi_k^2)(f_{k+1} - f_k), \tag{1}$$

where ρ is the density of the medium; v, spread velocity of the waves; k, index number of the filter in the frequency analyzer; n, overall number of filters in the analyzer; f_k, tuning frequency of the filters; and Φ, spectral amplitude of the velocity of the signal oscillations. In the calculations, it was assumed that the signal consists of transverse waves with a spread velocity of 3200 m/sec, and the density of the medium is 2.7 g/cm³. The next step is to reduce the values of the energy-flux density computed from Eq. (1) to the surface of a reference sphere with a radius R = 10 km using an empirical relationship to dampen the energy-flux density of the signal with a distance proportional to $R^{-3.6}$ [5]. In this case, the signal source of the center of the reference sphere was, in first approximation, placed at the center of the reference sphere was, in first approximation, placed at the center of the mine field. And, finally, this position of the center of the reference sphere for which the values of the energy-flux density of the signal, which were reduced to its surface, corresponded for all three observation points, was located by means of subsequent approximations. This position corresponded to the position of a certain conditional point source. In searching for the position of the source, we varied only the horizontal coordinates, as a result of which it should be considered that several conditional epicenters of signal sources were determined. Values of signal-emission energy were determined as the total energy flux through the surface of a reference sphere with a radius of 10 km. The result of the energy determination can be presented as follows:

The distribution of signals in terms of emission energy

$\lg E$, J	3	3,5	4	4,5	5	5,5
N	40	35	24	13	6	2

These data do not contradict the distribution of signals in terms of emission energy in accordance with the law

$$N = N_0 \cdot 10^{-\gamma \lg E},$$

in which the factor $\gamma = 0.5$. This relationship is also characteristic of the natural seismic process. The total emission energy of the 120 signals of "soft" seismic emission, which were recorded over a period of 52 days, amounted to $2 \cdot 10^6$ J on a reference sphere with R = 10 km. The positions derived for the epicenters of the emission sources are included within the bounds of the zone indicated in Fig. 1 by the cross hatching. A certain shift in this zone with respect to the position of the mine field is most likely caused by systematic error in determining the coordinates of the epicenters, which is generated by the assumption concerning the same damping of signal energy at all azimuths of their distribution.

DISCUSSION OF RESULTS

By its own vibration structure, in which appearances of longitudinal and transverse waves are not isolated, "soft" siesmic emission in the "Tashtagol'skaya" mine is similar to a greater degree to a volcanic tremor then to the low-frequency earthquakes observed in the deep mines of South Africa [6] (their recordings contain the appearance of longitudinal and transverse waves). Nevertheless, the outward similarity of the vibration processes is apparently insufficient as an explanation for their origin by the same mechanism. Thus, the resonance mechanism, which explains the volcanic tremor [7], assumes the presence of a high-Q resonator, where the vibrations are excited as a result of a blastlike pulse action. For a volcano, this resonator is a magmatic chamber, which has abrupt acoustic boundaries and which is filled with a material in which the damping of longitudinal waves is minor. An ore body excavated by a mine cannot be represented as a somewhat satisfactory resonator for seismic vibrations. Moreover, the presence of "rigid" seismic emission, together with "soft" emission directly contradicts the resonance hypothesis.

The results of spectral analysis of the "soft" seismic emission in the "Tashgol'skaya" mine make it possible to classify it formally as so-called soft or slow earthquakes. A distinguishing characteristic feature of these earthquakes is a relatively low emission energy with a large central zone [3]. A description of this type of phenomena is possible on the basis of Brune's model of an earthquake center [8], according to which an earthquake is the result of a sudden movement of rock masses along the rupture plane of the medium's continuity under the action of tangential stresses, the magnitude of which exceeds the shear strength of the medium. The basic parameter for this description is the seismic moment M_0. Its magnitude is proportional to the product of the area of the medium's failure and the average movement. In the general case, the seismic moment is defined in terms of the tensor of strains at the center of the earthquake; its scalar magnitude, which can be calculated using McGarr's empirical relationship between the moment and the emission energy [9], can be represented, however, for the approximate estimates made below:

$$\lg M_0 = 16.2 + 0.53 \lg E. \quad (2)$$

In the general case, the size of the seismic-emission center is inversely proportional to the angular velocity of its spectrum [10]. In Brune's model, the earthquake center is represented as a circle, whose radius r_0 is linked to the angular frequency f_0 of the spectrum by the following relationship:

$$f_0 = 2.34 v / 2\pi r_0, \quad (3)$$

TABLE 1

Mine	H, km	ΔV, m^3	ΣE, J	f_0, Hz	ΣM_0, dyn/cm	r_0, m	u_d, cm	Δb, bar	ΔV m^3
"Tashtagol'skaya"	0,9	$4 \cdot 10^4$	$2{,}0 \cdot 10^6$	3—6	$2{,}0 \cdot 10^{20}$	300—400	10^{-4}—10^{-2}	10^{-3}—10^{-1}	$4 \cdot 10^2$
in South Africa	3,2	$4 \cdot 10^3$	$0{,}8 \cdot 10^8$	4—30	$1{,}6 \cdot 10^{21}$	50—420	10^{-2}—1,2	0,5—43	$4 \cdot 10^3$

where v is the spread velocity of the waves.

The magnitude of the average displacement u_d at the center of the earthquake and the tangential stress $\Delta\sigma$ induced during the earthquake in Brune's model are determined by the following relationships:

$$u_d = M_0/\pi r_0^3 \mu \tag{4}$$

(where μ is the stiffness modulus of the medium), and

$$\Delta\sigma = 7/16 M_0/r_0^3. \tag{5}$$

McGarr [9] represents the development of earthquakes in connection with underground excavations in the following manner. The formation of an internal cavity in a prestressed mass leads to shear-stress concentration; this, in turn, gives rise to breaks in the continuity of the medium, the movement across which leads to filling of the excavated space. The total seismic moment ΣM_0 of the earthquakes that have occurred in this case will depend on the volume of the rock removal ΔV_r:

$$\Sigma M_0 = K\mu |\Delta V_r|, \tag{6}$$

where K is a coefficient ranging from 1/2 to 4/3, depending on the situation.

The parameters of the sources of "soft" seismic emission in the "Tashtagol'skaya" mine are given in Table 1 in comparison with the parameters of emission sources in a deep-level mine of South Africa [6], which can also be classified as a "soft" type on the basis that the angular frequencies of its spectrum are grouped around 10 Hz. Data of observations conducted over a 50-day period during which 123 events with emission energies ranging from 10^3 to $3 \cdot 10^5$ J were recorded in the "Tashtagol'skaya" mine, and 32 events with emission energies ranging from 10^5 to $4 \cdot 10^7$ J at the South African mine are given for comparison. The seismic-emission conditions in the mines are characterized by the depth H of excavation and by the volume ΔV of rock removed during the observations. The parameters measured directly were the total emission energy ΣE and the angular frequencies f_0 of its spectra. The remaining parameters given in the table (the total seismic moment ΣM_0, the radius r_0 of the emission region, the average displacemtne u_d with respect to the break, the induced tangential stress $\Delta\sigma$, and the volume of rock removed, which is equivalent to the seismic energy emitted ΔV_r) are determined from Eqs. (2)-(6). In the calculations, it was assumed that the "soft" seismic emission in the "Tashtagol'skaya" mine consists if transverse waves with a spread velocity v = 3200 m/sec. The density of the medium was assumed $\rho = 2.7$ g/cm^3, and the stiffness modulus of the medium $\mu = 3 \cdot 10^{11}$ dyn/cm^2.

According to the data presented in Table 1, the level of emitted seismic energy, which was averaged over a 50-day interval, for the "Tashtagol'skaya" mine is two orders of magnitude lower than the level of emission energy in the deep South African mine. If, however, we take the data, which were averaged over the last five years and which take into account vigorous mine shocks, whose energy reached 10^{10} J in some cases [12, 13], this difference is reduced to one order of magnitude. According to relationships (2) and (6), the seismic-emission energy is determined by the change in the volume of the medium. This condition is fulfilled for the deep mine for which the change in volume ΔV_r, which is equivalent to the energy emitted, is equal to the volume of the rock removed. For the "Tashtagol'skaya" mine, only 1% of the volume of rock removed is equivalent to the seismic emission. This result must be explained by the fact that not every filling of the cavities formed during underground excavations is accompanied by the emission of seismic waves. Where reference is made to the derivation of relationship (6) in [10], it can be stated that emission occurs when filling of the cavities is accompanied by rock failure. In the "Tashtagol'skaya" mine, the cavities that are formed after excavation of the ore are filled primarily due to collapse of the mass of the overlying rock with the formation of a crater on the surface. Collapse of the rock apparently occurs aseismically, since the deformations take place along prepared slip planes. Fracturing of the mass develops episodically with the accumulation of internal stresses, and is manifested in the form of a mine shock. In this case, two hypotheses can be expressed relative to the origin of the "soft" emission. Either it is associated with the process of rock collapse in a crater, and, in this manner, has no relation to the development of a strong mine shock, or there exists some relation between the collapse and mine shocks, which is difficult to represent within the framework of models of an earthquake center, on which the process of brittle rock failure is based.

In explaining what has been stated, it is possible to add that spectra of technogenic seismic emission, which is associated with underground excavations of mineral resources are, as a rule, of lower frequency than spectra of natural earthquakes of the same energy. In contemporary notions relating the emission of seismic waves to the brittle failure of rock [8], this means that relatively large center dimensions with smaller movements and induced stresses are characteristic for technogenic earthquakes. The seismic-emission parameters presented in Table 1 for the mine at the 3.2-km level make it possible to assume that it occurs as a result of brittle rock failure, but with the reservation that the waves are formed with the appearance of cracks, which are isolated one from the other and which do not merge into the main fracture [2]. One of the possible variants of this source is the so-called barrier model, which assumes that barriers of harder rock prevent crack development [14]. The evaluation of the magnitude of ground movements and induced stresses, which we performed for "soft" seismic emission in the "Tashtagol'skaya" mine (see Table 1), yields values of the order of hundredths and tenths of a bar. This is extremely difficult to accept combined with the statement that the cause of emission is brittle failure of the mass.

The phenomenologic theory yields a more flexible method of describing seismic emission as compared with the brittle-fracture model. Its basic positions are given by Gusev [15]. In this theory, the earthquake center is represented as a complex system consisting of a large number of subcenters, the emission from which is mutually related by time. In this case, the oscillations recorded are the result of the noncoherent superposition of emissions from the subcenters. The characteristics of this system (the size and number of the subcenters, the spectra of their emission, and the volume of the medium, occupied by the subcenters) are determined by spectral analysis and by the method of constructing synthetic seismograms. It is possible that use of this theory in the investigation of "soft" seismic emission will lead to the notion concerning the process of the development of a strong mine shock. The premise to this is the fact that up to two angular frequencies, whose values are interpreted as characteristics of the magnitude of the emission region and the predominating size of subcenters, are isolated on the "soft"-emission spectrograms presented in Figs. 3b and c. In this case, the dissimilarity of the signal spectra recorded at different distances from the source, and the absence of a second angular frequency in the signal spectra recorded at the near point are explained by the fact that the near point is actually inside the emission region, and the effect of division into subcenters is not observed there. The notion concerning the fact that the center of technogenic seismic emission may consist of a number of sources isolated one from the other is by itself confirmation in the description of the action of a strong mine shock [16]. It is noted in this description that failure during a mine shock occurred in individual segments between which the spaces remained undisturbed.

Seismic observations in the "Tashtagol'skaya" mine from July through September, 1983 indicated that "soft" emission in the form of low-frequency signals reminiscent of a volcanic tremor predominated at that time. The duration of the signals ranged from three to 20 sec, and the average frequency of recurrence was 2-3 times per day. The distribution of signals based on emission energy corresponds to the slope of the frequency curve $\gamma = 0.5$. Analysis of the energies and frequency spectra of the recorded signals indicated that their emission may not be satisfactorily described on the basis of notions concerning the brittle failure of rock in view of the ulikely small ground motions and induced stresses estimated from Brune's model. In addition to this, the presence of a second angular frequency in the spectrum of recorded signals creates certain grounds for modeling "soft" seismic emission using the phenomenologic theory, which assumes that waves are generated by a large number of sources linked one to the other by certain correlation relationships. Similar modeling is also most likely applicable to strong mine shocks.

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