A scheme for the preparation of strong induced seismic events

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Abstract
A scheme of rockburst preparation is proposed from an analysis of induced seismicity.«Rigid» inclusion is the basis of this scheme. Intensive destruction of the inclusion begins when a critical flaw concentration is reached in the volume. The size of the inclusion volume before destruction determines the maximum possible rockburst energy. It is very difficult to determine the place, where the main discontinuity will propagate, thus rockburst location may be determined only within the accuracy of a nucleus-zone size. The results obtained show: a) maximal localization of the failure process in a space occurs during the preparation of the dynamic event, and localization of the failure process in a time follows; b) the period of preparation of a high energy event has discontinuity values scatter less then during the subsequent period; c) both the average size of discontinuity and its variation ratio have good forecasting capability.

Key words *induced seimicity – rigid inclusion – rockburst*

1. Introduction

One of the most difficult problems in seismic event forecasting is time prediction. However, time prediction requires a better understanding of the processes which take place in the Earth's crust in order to create a model and scheme of the preparation of seismic events. Unlike laboratory experiments, methods of monitoring, data acquisition systems and telemetry in mines are limited. Hence the scheme of rock failure, which we consider below, is based only on the recording, processing and analysis of mine-induced seismicity.

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2. Physical basis for the preparation scheme of mine-induced strong seismic events

Let us consider the physical aspects of the preparation of induced seismic events using the concepts first formulated by Dobrovolski (1983, 1991, 1992). He claimed that the earthquake process involves the origin and evolution on a discontinuity (inclusion) against the background of initial state of the medium. The basic concepts of tectonic earthquake preparation describe an earthquake as a result of fracture within the Earth's crust. There are three general conditions which define the capability of the crust for an earthquake:

1) Intensive and permanent deformation, the source of which is assumed to be the motion of material.
2) Block structure with fault zones.
3) The presence of high tangential stresses.

It is assumed here that the earthquake is not a sudden event, and that its preparation process is local.

The description of the preparation of a seismic event is based on the following principles:

1) A single event determines the parameter values of the mechanical process.

2) The disturbance are calculated.

3) The boundary conditions are formulated.

Earthquake forerunners are defined as geophysical field variations which are caused by the local earthquake preparation processes. There are two stages in the evolution of discontinuity – the beginning and the development, and the destruction culminating in the formation of the main fault.

An analysis of induced seismicity data from the North Ural Bauxite Mine 15-15′ (NUBM) was carried out and the «rigid» inclusion model was proposed, in order to describe the preparation and relaxation process of induced seismic events (rockbursts). This model was developed and improved using the kinetic approach to the strenght of solid (Regel *et al.*, 1974; Petrov, 1984). According to the kinetic approach, the failure process of a stressed solid consists of two main stages. First, a critical concentration of cracks is reached in the solid as a necessary condition for the process to proceed to the next stage. This condition is fulfilled when the average space between cracks becomes equal to three times the crack size (Zhurkov *et al.*, 1981). The scheme for forecasting failure is based on both the two-stage model and the concentration criterion, and is rather simple if the crack concentration is known at the time when the observations start (Kuksenko *et al.*, 1987; Mansurov, 1993).

3. Induced seismicity concentration characteristics and seismoactive volume changes during strong rockburst preparation processes

The reasoning which follows is based on an analysis of changes in the size of the seismoactive volume, and the crack concentration in it, according to the number and location of the cracks. The following concentration characteristics are proposed for the seismic regime in mines: the geometrical (3D) volume occupied by typical seismic events (km^3); the concentration or 3D volumetric density of events, *i.e.* ratio of the number of events to the 3D volume size (km^{-3}); the 4D volume occupied by the seismic events in space-time ($km^3 \cdot days$; the 4D concentration or 4D volumetric density of events, *i.e.* ratio of the number of events in the sample to 4D volume size ($km^{-3} \cdot days^{-1}$); concentration parameter, which is equal to the average space between events hypocentres divided by average crack size.

Figure 1f shows that most high energy seismic events in mine field 15-15′ NUBM were recorded in the first half of the chosen observation period; induced seismicity was relatively quiet during the second half of the period. There were four strong events with energy of 10^8 J (8-th energy class events). Generally, the concentration characteristics change in a complicated way. Nevertheless, certain regularities exist which repeat for all considered events (fig. 1a-f). Approximately 3 or 4 months before a strong event, the low energy crack concentration begins to grow. 40-50 days before the event, the crack concentration increases rapidly. For some time after the relaxation, the crack concentration may remain at the same high level. Then a downward slope of concentration followed by new rapid increasing is observed (fig. 1b,d). After that, the crack concentration slowly decreases to its lowest values for a period of a few months or even a half year. Thus, the preparation process for a strong event is in a good agreement with the general concepts of a formation and destruction of a «rigid» inclusion as mentioned above. That is, in a certain area of the rock massif, mining can create the conditions for concentrated development of the deformation processes. The medium becomes more «rigid» in this area, *i.e.* a discontinuity is formed. The discontinuity size increases with time, occupying new medium zones. Thereby, the stress acting on the discontinuity volume grows, which leads to the activization of cracking within it. The process of discontinuity formation is illustrated well on fig. 1a.

The destruction of a discontinuity was not described in the scheme of tectonic earthquake preparation and realization. We fill this gap by applying the kinetic concepts of solid failure.

Figure 1a shows that the «rigid» discontinuity destruction process consists of more then

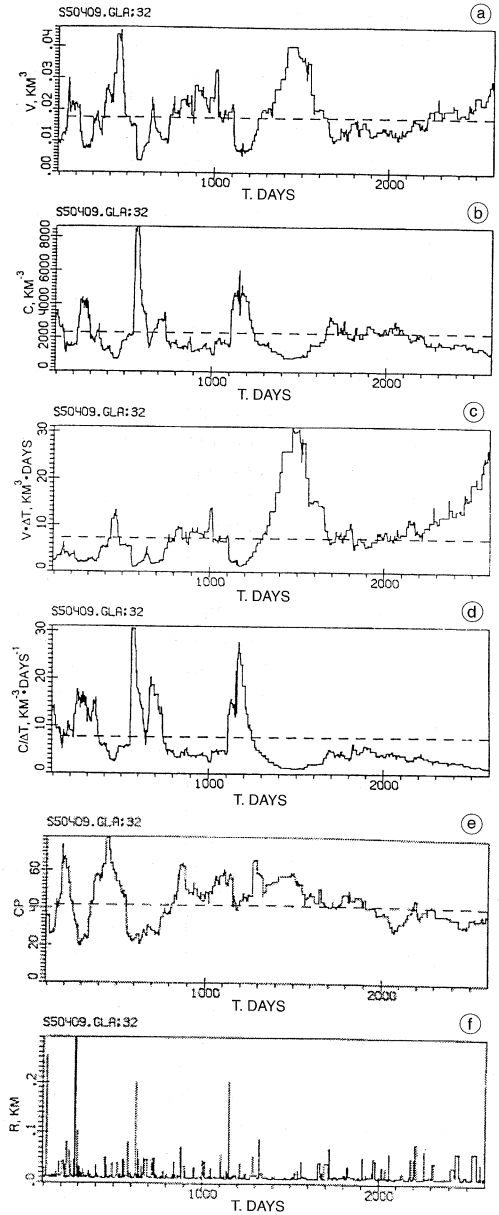

Fig. 1a-f. Changes with respect to time in: a) the three-dimensional seismoactive volume (V); b) the event concentration (C); c) the four-dimensional seismoactive volume ($V \cdot \Delta T$); d) the event concentration in four-dimensional volume ($C/\Delta T$); e) the concentration parameter (CP); f) the time-sequence of seismic events (R – cracks length).

one stage. A final discontinuity failure takes place when a crack is formed with a size the same as the discontinuity.

Thus the long-term forecasting of a failure time is connected with the ending of the discontinuity consolidation stage and the beginning of its destruction stage. Available results allow us to estimate the duration of the consolidation stage. For 8 energy class events it is 100-200 days. The time during which an event concentration in seismoactive volume attains maximum values (about 45-60 days) can be used as forerunner to make mid-term forecasts. The seismoactive volume takes on a minimal size due to the localization processes in discontinuity nucleus area. Rough estimates define the size of a discontinuity nucleus as 10 times less then the whole local volume of discontinuity. Crack concentration increasing in a nucleus leads to crack enlargement, and to instability of failure nucleus as well. The nucleus extends its boundaries in the plane of imminent macrofailure (Anikolenko and Mansurov, 1996). That appears as a seismoactive volume enlargement and event concentration decrease just before the instant of macrofailure. The instability stage in the failure evolution process begins when the event concentration in the nucleus stops growing but the nucleus volume size begins to grow. This stage can be used to make short-term forecasting. At this period the seismoactive volume takes the form of imminent macrofailure.

The «rigid» inclusion model lets us reach a significant improvement in forecasting quality when the statistical characteristics of the failure process are also controlled.

4. Induced seismicity static and dynamic component changes during strong rockburst preparation processes

It is useful to derive two components of induced seismicity: the static component and dynamic components. The first can be represented by the expected or average values of parameters of induced seismicity and the second by the dispersion, standard deviation and variation ratio.

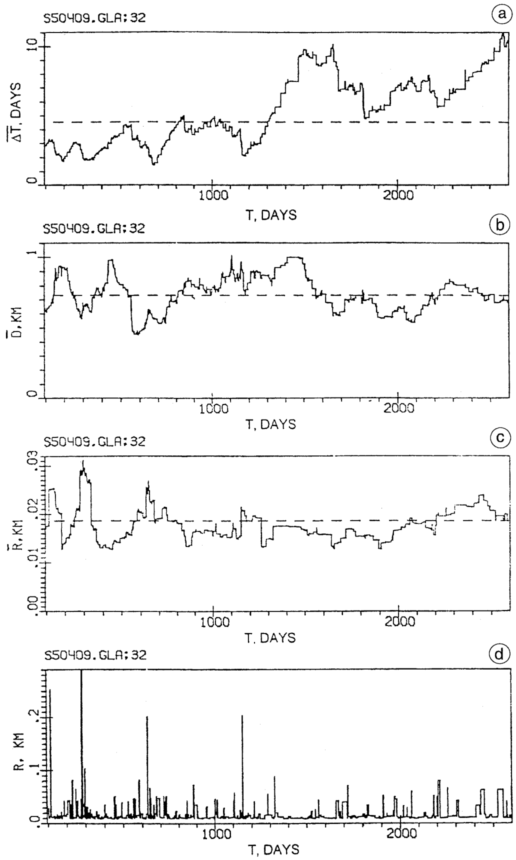

Fig. 2a-d. Changes with respect to time of: a) the inter-event average time ($\overline{\Delta T}$); b) the average space intervals ($\bar{D}$); c) the crack average length of cracks ($\bar{R}$); d) the time sequence of events (R – cracks length).

Analyzing with respect to time the changes in both the time-space intervals between chronologically successive events and the average values of the formed crack size showed that the average inter-event times of 4-8 energy class events take values from 1.5 to 11 days. The shortest inter-event times were observed during 50-100 days after the large cracks appeared with an energy of about 10^8 J (fig. 2a). The average space between successive events, which forms a spatial event stream, changes from 240 m to 1 km (fig. 2b) and decreases during the preparation of a strong event.

It was found that the period of time and space localization do not coincide (fig. 2a,b). Space localization occurs before high energy events while time localization occurs after. Hence, the main condition of brittle fracture of the rock is the space localization of the failure process.

The average crack size $\bar{R}$ increases gradually for 100-200 days before a strong event. The value decrease for about the same time after the event. The parameter $\bar{R}$ has a better sensitivity to imminent strong events against inter-event time and average spatial interval (fig. 2a-d).

Both the standard deviations and variation ratios of induced seismicity parameters (dynamic component of random process), and the average values of seismicity parameters (static component), undergo nearly the same changes with respect to value and behaviour during the entire observation period.

The variation ratios of the characteristics mentioned above have been assumed to be important for forecasting. In particular, importance has been attached to the increase in the variation ratio of time-space intervals between discrete fracture events (Mansurov, 1995; Tomilin and Voinov, 1995). However, analysis of the characteristics behaviour during the preparation of strong events shows an absence of any invariant changes connected with rockburst preparation. One may note that the preparation of a high energy event is characterized by a small scattering of the sizes of cracks; this increases after the occurrence of the event (figs. 3a-c and 4a-c).

Thus, the results obtained allow us to visualise the preparation and relaxation of strong mine-induced seismic events as a process of the origin and decay of a «rigid» inclusion occurring in the deformed rock massif, and proceeding according to kinetic laws.

5. Scheme for the preparation of a strong rockburst

A generalized of typical changes in deformation rate $\dot{\varepsilon}$, discontinuity volume V, cracks concentration C, the concentration parameter CP and the activity $\dot{N}$) during the activization

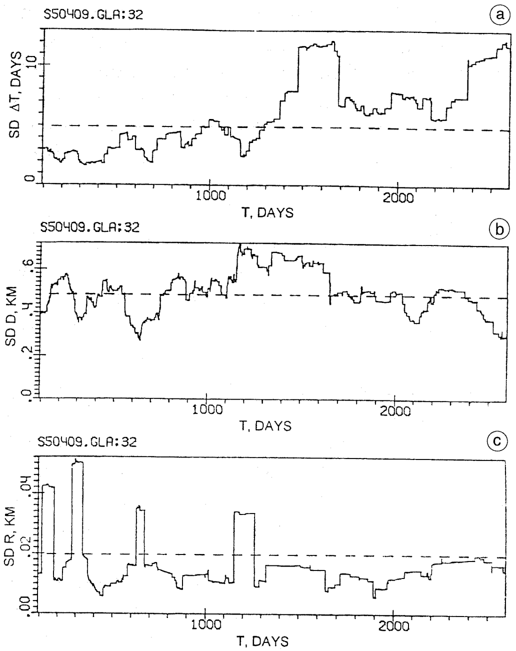

Fig. 3a-c. Changes with respect to the time of the standard deviation of: a) the inter-event time (SD ΔT); b) the space intervals (SD D); c) the crack length (SD R).

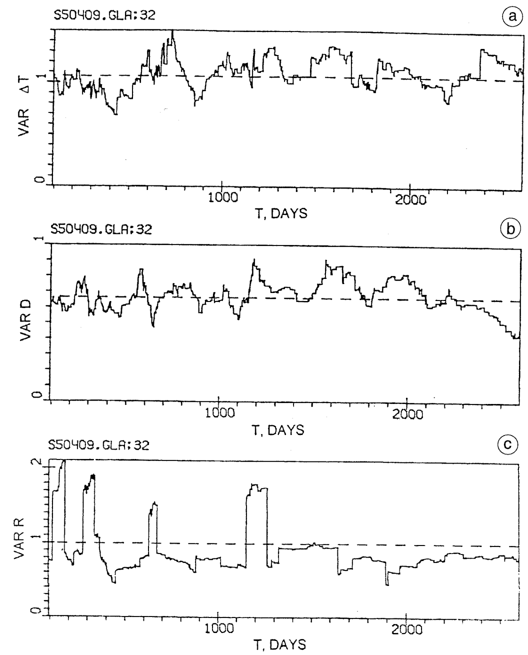

Fig. 4a-c. Changes with respect to time of the variation ratio of: a) the inter-event time (VAR ΔT); b) the space intervals (VAR D); c) the crack length (VAR R).

period (400-800 days) of a strong rockburst in the 15-15′ mine field (NUBM) is illustrated in fig. 5a-d. Taking the above discussion into account, it is possible to propose a generalized scheme of the preparation of a strong rockburst.

One may consider that at time t_1 at any location in a deforming massif there is an inhibited deformation process. This impediment will cause a decrease in the deformation rate and an increase in stress in some neighbouring areas. Thus the stress-strain state will be disturbed, and will spread through some massif areas. Cracking will be activated by the increasing stress within the discontinuity boundaries. This process reduces the rapid stress growth and restricts the discontinuity volume. At a later time t_2, the discontinuity volume stops the growing. This occurs when the discontinuity compaction caused by the increasing stress is balanced out by the dilatation which is produced by cracking. After this time the dilatation and discontinuity destruction are intensified. The reason for this is the active crack enlargement, which will also cause an increase in the deformation rate, and a stress drop within the discontinuity volume. In general, crack enlargement occurs along a future macrofailure line. At time t_3 the deformation rate rapidly increases and a shock occurs with an abrupt increase in deformation. In the vicinity of the displacement stress and the direction of deformation can change sign. An abrupt change in deformation and a redistribution of stress in the displacement area can then initiate a process of crack enlargement in the surrounding volume. This volume has a high crack concentration and is well prepared for fracture development. After time t_4, the relevant characteristics begin to return to their background value. Thus there are three main stages in the evolution of a rigid inclusion: first, the forming or consol-

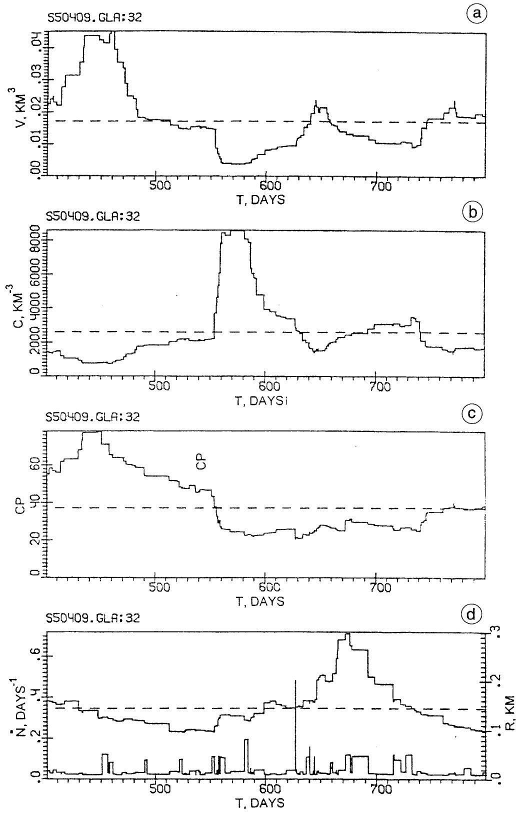

Fig. 5a-d. Changes with respect to time during a 400-800 day observation period: a) the seismoactive volume (V); b) the event concentration (C); c) the concentration parameter (CP); d) the seismic activity (N).

idation of the discontinuity ($t_1 - t_2$); second, the destruction of the discontinuity ($t_2 - t_4$), which includes the main fault occurence ($t_3 - t_4$); third, the post failure stage ($t_4 - t_5$).

The changes in characteristics (fig. 6) during the preparation and realization of a rockburst proceed as follows:

1) When the discontinuity is formed, the rock deformation rate can decrease substantially in comparison with its background value, and can even reach zerolevel. Later, the deformation rate grows due to stress increase and cracking activity. During the consolidation stage the volume of the discontinuity and the internal stress increase. This is reflected in the physical and mechanical properties of the rock. For instance, the velocity of elastic waves increases. In this paper, volume increase is judged by the average distance between chronologically successive seismic events. As the stress grows within the discontinuity volume, this leads to cracking activation, and is especially noticeable at the final moment of the first stage.

At the same time, the growing rate of the discontinuity volume exceeds the rate of increase in the number of forming cracks. This leads to a decrease of the crack concentration within the discontinuity volume, and an increase in the concentration parameter CP. (CP is the ratio of the average space between hypocentres to the average size of cracks). The consolidation stage ends when the deformation rate begins to increase due to rapid crack enlargement and the localization of cracks in an area of imminent macrofailure. The increasing deformation rate leads to both a stressdrop in the rock massif, and a decreasing number of cracks being formed.

2) After time t_2 the process passes to a stage of discontinuity destruction. The deformation rate continues to increase and the discontinuity volume decreases rapidly due to intensive localization of process in the area of the future fault. This results in a sharp growth of event concentration and a decrease in the concentration parameter.

At the time of main shock, t_3, the volumetric concentration of events reaches a maximum magnitude, and may then decrease slightly, which is explained by the extention of the macrofailure area. At the time of the main shock, a rapid displacement of fault surfaces take place, accompanied by an abrupt growth in the deformation rate. Then follows a similarly abrupt halt, and the deformation direction changes if the displacement magnitude is more than necessary to return to the equilibrium state.

The process of discontinuity destruction ends at the time when the main displacement stops. After this moment, (t_4), comes the aftershock period, and the stage of recovery of the physical characteristics of the rock in the vicinity. The most active stage of discontinuity destruction is characterized by a significant increase in the cracking rate, and intensive crack enlargement.

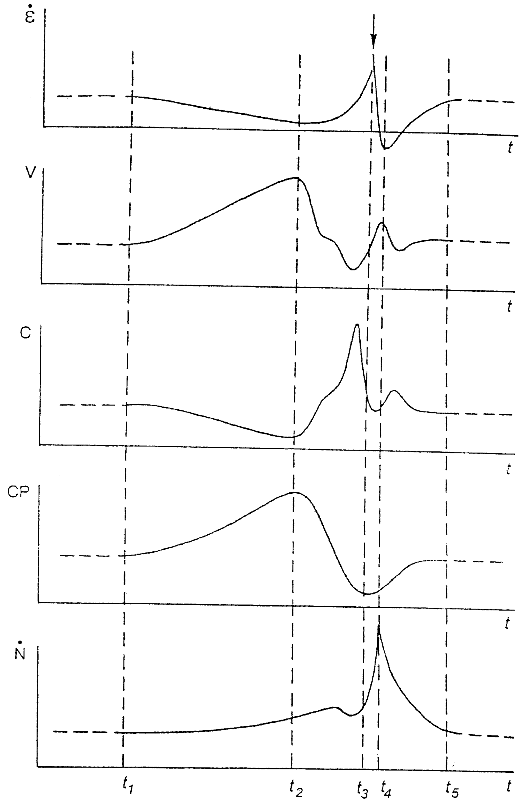

Fig. 6. Changes in characteristics, in accordance with the proposed rockburst model: deformation ($\dot{\varepsilon}$), seismoactive volume (*V*), event concentration (*C*), concentration parameter (*CP*), seismic activity ($\dot{N}$).

At time t_4, a peak of seismic activity and a small increase in the active volume are observed. This leads to a decrease in the concentration of further events in the area of macrofailure. This rock massif then returns to its normal state, and its characteristics take the background values again.

6. Conclusions

The process of preparation of strong rockbursts is local, and proceeds according to rigid inclusion (discontinuity) development scheme, the intensive destruction of which begins after the critical concentration of cracks in seismoactive discontinuity volume is reached.

The discontinuity volume at the moment when destruction starts determines the maximum possible energy of the main seismic event.

The higher the event energy is, the greater the uncertainly in forecasting the place where faulting starts. That is, the location of an expected rockburst or an induced earthquake can be determined with accuracy up to the size of the nucleus zone, the shape of which should be close to an ellipse, disk or parallelepiped. Thus, the smaller the thickness of the nucleus zone is, the closer the macrofailure.

The dynamic component of induced seismicity is proportional to the static component. The maximum spatial localization of failure process comes during the seismic event preparation, and the temporal comes later.

The period of high-energy event preparation is characterized by smaller scatter of the formed faults sizes, than in the subsequent period.

The average value of faults $\bar{R}$, has good forecast capability.

REFERENCES

ANIKOLENKO, V.A. and V.A. MANSUROV (1996): Invariant kinetic approach to the description of a rock fracture process and induced seismic events, *Pageoph,* **147** (2), 367-375.

DOBROVOLSKI, I.P. (1983): Earthquake preparation. Deformation and size of forerunners appearance zone, in *Experimentalnaya seismologiya* (Nauka, Moscow), (in Russian), 17-25.

DOBROVOLSKI, I.P. (1991): *Theory of Tectonic Earthquake Preparation,* Institute of Earth Physics, Moscow, AN SSSR (in Russian), 217, 257.

DOBROVOLSKI, I.P. (1992): Theory of strong tectonic earthquake preparation, *Earth Physics,* **6**, 31-47 (in Russian).

KUKSENKO, V.S., I.E. INJEVATKIN and B.TH. MANJIKOV (1987): Physical and methodical foundation of rockburst prediction, *FTPRPI,* **1**, 9-22.

MANSUROV, V.A. (1993): Laboratory experiments: their role in the problem of rockburst prediction, in *Comprehensive Rock Engineering (*Pergamon Press), vol. 3, 745-771.

MANSUROV, V.A. (1995): Investigation of process of rock failure using AE for prediction of dynamic events, in *Proceedings of the Fifth Conference «AE/MA in Geological Structure and Materials. Series on Rock and Soil Mechanics»* (Trans. Tech. Publications, Clausthal, Germany), vol. 19, 59-72.

PETROV, V.A. (1984): Theoretical foundations of failure micromechanics, in *Readings in Commemoration of A.F. Ioffe* (Nauka, Leningrad), 22-28.

REGEL, V.R., A.I. SLUTSKER and E.E. TOMASHEVSKI (1974): *Kinetic Nature of Strenght in solids* (Nauka, Moscow), pp. 560.

TOMILIN, N.G. and K.A. VOINOV (1995): Technique and results of the rockburst prediction, in *Proceedings of the 2nd International Conference MJFR «Mechanics of Jointed and Faulted Rock»* (Balkema, Rotterdam), 955-959.

ZHURKOV, S.N., V.S. KUKSENKO and V.A. PETROV (1981): Physical principles of mechanical failure prediction, *Doclady AN SSSR*, **259** (6), 43-50.