Similarities between strong rock bursts with fault-slip mechanism and induced earthquakes

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Abstract. Common features within manifestation of strong rock bursts with fault-slip mechanism and induced earthquakes that are studied in this paper are: correlations between the direction of the major fault wall displacement caused by geodynamic events and the regional stress field; typical correlations between the size of the focal zone and the hypocentre depth; locations of seismic hypocentres deeper than the depth of mining activity, and at distance from mining districts. Consideration is given to the direction of the major fault wall shifting in relation to strong tectonic shocks and induced earthquakes; the size of focal zones and their correlation with the size of geodynamically active crustal blocks; the location of the geodynamic event hypocenters relative to zones of anthropogenic impact. The similarity in manifestation of strong rock bursts and induced earthquakes is explained by the interaction of local and regional (global) geodynamic processes. The critically stressed state of the Earth's upper crust, which has a block-hierarchical structure, is assumed to be the fundamental premise for such causality interaction.

1. Introduction

The problem with strong rock bursts and mine related earthquakes (mining seismicity) remains one of the hottest issues in mining areas [1-4]. In this article, the term “strong rock bursts” means events with a fault-slip mechanism and an energy class of $E = 8$–9 and above, which generally corresponds to the existing rock burst classifications, for example [3, 5-6]. The ability of miners to manage these hazards is often limited due to the fact that the hypocenters of events are located outside the mining districts, sometimes outside the mine lease or at greater depths [7-9]. The anthropogenic nature of strong seismic events with a great hypocentre depth which are in places where there is intense human impact on the underground resources, is widely discussed. The key argument against presumable technogenic genesis of strong earthquakes is high energy and great hypocentre depth. Thus, D. Simpson and W. Leith [10] classified earthquakes in 1976 and 1984 in the Gazli gas deposit, with a magnitude of 7 and hypocentre depths of 10-15 km as induced events, since their epicentres were located within the mine field. However, [9] (R. Bossu et al. (1996)) believed that such strong earthquakes with deep hypocentres cannot be related to human activity, as the stress changes at great depths are too insignificant. Similar discussions revolve around the nature of the Buchatsky earthquake which occurred near a coal pit in Siberia (Kuzbass) with a magnitude of 6.1 and hypocenter depth of about 4 km [8]. The data available on strong rock bursts and induced earthquakes in industrial regions make it possible to outline some common features within their manifestation. The purpose of this work is to analyse the features of these geodynamic phenomena using the concept of the critically stressed state of the earth's crust, which would facilitate the search for consistent patterns and the development of recommendations on safe mining practices.
2. Theoretical concepts and method

2.1. Interaction of local and global geodynamic processes
In the second half of the 20th century, mining practices revealed zoning in the manifestation of hazardous geodynamic and gas-dynamic phenomena within mines. The results of experimental studies on undisturbed rock stress state [11, 12] have appeared, indicating the exceedance of horizontal stresses over vertical ones. The stressed state of the rock is recognised as one of the key factors indicating the rock burst risk [3,7, 13]. In tectonics, insight into block structure of the earth's crust was offered, and the concept of the stress fields hierarchy was contributed to geophysics. On this basis, methods of geodynamic zoning was developed in Russia. Prof. Batugina I.M. and Petukhov I.M. in their works pioneered the idea of interactions between local geomechanical and global geodynamic processes. They also proposed a block-hierarchical model of the rock mass. It was proposed to use available cartographic material to identify earth's crust blocks of four hierarchical ranks for mine fields, take into account their interaction to assess the stress state of the in-situ rock mass and offer recommendations aimed at safe mining practices [7]. Further studies have shown the worthiness of the geodynamic zoning concept and method which has led to ideas about the extremely stressed state of individual areas of earth's crust.

2.2. Critically stressed state of the earth's crust
The concept of the critically stressed state of the rock mass is widely used in mining geomechanics, e.g. when describing ground pressure, analysing mechanisms and measures to mitigate rockbursts. Part of the abutment pressure zone from the face to the area of its maximum (X1 in Figure 1) is in an extremely stressed state, whereas the zone in the depth of the massif, beyond the maximum abutment pressure, is in an elastic state.

![Diagram](image)

**Figure 1.** Critically stressed zone near the face [7].

In the zone of maximum abutment pressure, the rock mass is acquiring the critically stressed state. The stress \( \sigma_y^0 \) at the face line corresponds to \( \sigma_{cr} \) of the rock mass and it increases to a certain maximum value due to the rock strengthening under triaxial compression. The transition of the rock to the ultimate stress state is accompanied by the emission of seismic impulses arising from rock failure and movements along the fracture surfaces. The critically stressed zone is understood as an area where stress has reached the maximum bearing capacity of the rock, rather than the zone of eroded coal (rock). Therefore, the impact on this zone from the face, for example, penetration of the shearer/cutter, blasting, etc., immediately causes changes in this critically stressed zone. The additional load is transferred deeper into the rock mass, and the maximum bearing capacity of the rock is also shifted there. With the shift of the maximum bearing capacity into the depth of the rock mass a new part of the rock acquires a critically stressed state and seismic energy is emitted. Although the coal seam is in
an excessive stress state, it retains the ability to accumulate the potential energy of elastic compression, which is proportional to the square of the effective stress values.

The development of the geodynamic zoning concept led to the idea of the critically stressed state of the earth's crust from its surface to a certain depth [7]. Since the maximum compression in the earth's crust is oriented mainly horizontally, then, according to the hypothesis of prof. I.M. Petukhov, the stress distribution pattern in its upper part is similar to the stress distribution around the coal face. Near the surface, the stresses correspond to the $\sigma_{\text{c,j}}$ of the rock, whereas the maximum stress zone is located at a certain depth, depending on the conditions of interaction between the crustal blocks.

A critically stressed zone in the earth's crust upper part is understood as an area with an extremely discrete distribution of stresses, where areas (blocks) in an extremely stressed state alternate with relatively unloaded areas, yet being located within a certain layer of the earth's crust. Such concepts of the geodynamic system state such as "block rock mass" makes it possible to explain a number of common features in the manifestation of strong rock bursts and induced earthquakes.

3. Common features in the manifestation of strong rock bursts with fault-slip mechanisms and induced earthquakes

3.1. The direction of the major reactivated fault wall displacements is controlled by the regional stress field

Mining operations cause stress redistribution and reactivation of tectonic faults. Shear displacement of the reactivated fault walls in the earthquake source is one of the common features in the manifestation of strong rock bursts, in both induced and natural earthquakes. Rock bursts with shifting fault walls (their reactivation) were named "fault slip", "slip burst", “tectonic rock burst”. The direction of the reactivated fault walls shifting is linked with the altered technogenic stress field [14]. However, it was noted that in cases of strong rock bursts, the displacement direction of the major reactivated fault walls were comparable to the size of the mine fields, and were controlled by the regional stress field [15], Figure 2a. This effect is explained by the interaction of local and regional (global) geodynamic processes: under the influence of mining operations the planes of fault displacement get unloaded with subsequent realisation of the modern tectonic process, in which large crustal blocks participate.

Similar tectonophysical models are also used to explain the mechanisms of strong induced earthquakes. For example, in [16], the reactivation of the Alhama de Murcia fault was explained by the influence of groundwater drainage. However, the displacement along the fault in this model is also controlled by the regional stress field, Figure 2b.

![Figure 2. Tectonophysical diagram of a strong rock burst [15] and induced earthquake [16], with the author's remarks.](image)

3.2. Location of strong rock burst hypocenters and induced earthquakes at greater depths or far from anthropogenic impact

The effect of strong rock bursts and induced earthquakes with hypocenters located at depths much greater than the depths of mining or other anthropogenic impact, and/or at a distance, is well known and widely manifested.
Below are some examples
- Severouralsk bauxite mine 15-15: strong rock burst, 10^8 J, was recorded on 02/20/1987 in an area where mining operations had ceased 15 years earlier.
- The hypocenters of strong rock bursts at the Tkibuli-Shaorsky field, SUBR, and many deposits elsewhere globally were located below the mining area, sometimes at a depth of 2 km or deeper.
- Cernic, 1964 gives an example of a strong rock burst on October 15, 1929 at the Tyrol mine (Austria). The rock burst occurred at levels VIII and IX in the area where no works had been carried out for about 55-60 years.
- On October 22, 1930, an extremely strong rock burst occurred in the footwall at the VII eastern level, near the 1st Southern fault, where no one had worked for 42 years.
- Strong rock bursts were recorded in the mines of the Kolar deposit: on June 11, 1959, on March 19 and 30, 1960, and on March 27, 1961. The centers of these events were far away from the ore vein (Krishnamurthy, 1969, Taylor, 1963) [17].

The same effect is typical for anthropogenic earthquakes. The depth of the Bachatsky earthquake hypocenter is estimated at 4 km, while the depth of the coal pit was only 300-320 m.

3.3. Correlation between the size of the focal zone and the hypocenter depth.
Another common feature in the manifestation of strong rock bursts and induced earthquakes is that the focal size of these geodynamic phenomena L are comparable or even exceed the depth of their hypocenter H (Table 1).

Table 1. Strong rock bursts and induced earthquakes: correlation between the size of the focal zone L and the hypocenter depth H.

| No | Event                        | Energy | H, hypocenter depth, km | Source | L, focal zone size, km | r = L/H |
|----|------------------------------|--------|--------------------------|--------|------------------------|--------|
| 1  | South Urals, 1990            | E=10.5 | 0.25                     | [18]   | 0.67                   | 2.2    |
| 2  | Lovozerskoye field, 1999     | E=8.7  | 0.3                      | [18]   | 0.79                   | 2.6    |
| 3  | Verkhnekamskoe field, 1995   | E=10.1 | 0.3                      | [18]   | 0.55                   | 1.8    |
| 4  | Beipiao, China 1973,         | M = 4.3| 0.5-1                    | [15]   | 1.0                    | 1-2    |
|    | Bachat coal pit,             |        |                          |        |                        |        |
|    | 2013                         |        |                          |        |                        |        |
| 5  | Kolyvanskoe, 2019            | M = 4.9| 2                       | [19]   | 2.6                    | 1.3    |
| 6  | Neftegorsko, Sachalin, 1995  | M=7    | 18-20                    | [20]   | 42                     | 2      |
| 7  | Gazly, Uzbekistan, 1976      | M_s = 7| 10 (1984); 16 (1976)     | [10]   | 42                     | 3-4    |

While the L/H ratio from [18] might be overestimated, as the depths of the hypocenters of rock bumps and seismic events are identical here, it can be seen that in many cases of strong rock bursts and induced earthquakes the ratio r = L/H is unity or even more..
4. Discussion
The common features in the manifestation of strong rock bursts and induced earthquakes listed above can be explained through the concept of the critically stressed state of the upper crust.

One of the symptoms that the upper part of the earth's crust is critically stressed is the fact that the hypocenter depth and the focus of the geodynamic event are proportional. Considering the source of a geodynamic event as a zone of failure and, accordingly, the zone of the critically stressed state of the rock, it can be seen that when the ratio between the radius of the source zone and the hypocenter depth is more than one, the source zone, i.e. the zone of the critically stressed state is located at a certain depth in the rock mass from the earth's surface [15]. For example, Figure 3 shows the layout of the sources of the Bachatsky earthquake in Kuzbass (a) and the Gazli earthquakes in Uzbekistan (b). Obviously, the focal areas of these events reached the earth's surface and were located directly in the zone of technogenic impact on these areas. Similarly, Figure 2b shows that the earthquake focus in Lorca, (2011, Spain) reached the area of anthropogenic drawdown of groundwater.

![Figure 3](image)

**Figure 3.** The layout of the induced earthquakes seismic focus (from the surface to a certain depth): a - Bachatsky earthquake, according to [15]; b - earthquake in Gazley, according to [9, 12], with the author's remarks.

The sign that the focal zone reached the earth's surface is the presence of fissures and dislocations on it. So, after the rockburst in 1999 at the Lovozerskoye field, a 1 km fracture was identified on the surface [18]. After the 1990 rockburst, fractures appeared on the surface at the Kurgazak mine. The study in the epicenter of the Neftegorsk earthquake (1995) revealed a 40 km long dislocation [20]. In such situations, mining or other activity affecting the rock mass and the earth's surface makes a direct impact on the critically stressed regional zone.

Here it is appropriate to quote the definition of a rock burst proposed by prof. Petukhov I.M.: “Rock burst is a brittle failure of the critically stressed part of rock (coal seam) adjacent to a mine excavation, which occurs under conditions when the stress state change rate in this part exceeds the critical stress relaxation rate in it”. If we assume that in some areas of the crustal upper part the critically stressed state has been reached, that is, the first condition for the geodynamic event initiation is fulfilled, then the second condition is induced by human activity.

One of the reasons for the observed effect of why hypocenters of strong rockbursts and man-made earthquakes are located at much greater depths than the depths of mining operations or other anthropogenic impact, as well as at some distance, seems to be the fact that human activity activates both faults and also crustal blocks. Thus, according to the geodynamic zoning carried out in Kuzbass in the 1980s, there is a spatial coincidence of block boundaries with areas of seismic activity around Polysaevo, located at a distance from mining districts and at 2-3 km depth.

Under such conditions when the size L of a rock burst and induced earthquake focus reaches hundreds of meters or several kilometers, the preparation zone R covers many kilometers, is commensurable with the crustal blocks G and exceeds the zone of induced impact of mining excavations, Figure 4.

Hence, displacement along large faults is realised as part of the tectonic process, i.e. the direction of displacements along these planes during strong rock bursts correlates with the regional stress field.
Assessment and analysis of the risk that a geodynamic hazard might be realised far from mining areas demands a theoretical comprehension, as well as knowledge of experimental works [21, 22]. It is of great importance not only for mining, but also when making decisions on such issues as reuse of abandoned mine workings [23], open-pit mining [24], waste disposal [25] etc.

Figure 4. Location diagram of presumptive preparation zone of the Bachat earthquake.

5. Conclusion
Common features in the manifestation of strong rockbursts with fault-slip mechanism and induced earthquakes that have been analysed in this paper, such as the displacement of the major reactivated fault walls controlled by the regional stress field; the location of rock burst and induced earthquake hypocentres at greater depths or away from the anthropogenic impact; correlation between the size of foci and depths of hypocenters, could be interpreted using the concept of the critically stressed state of the earth’s crust.

Crustal blocks involved in the modern tectonic process make up highly stressed zones extending from the surface to a certain depth. Due to technogenic impact on such zones new areas of the earth's crust get critically stressed, which triggers seismic process with hypocenter depths much greater than the depth of the technogenic impact area. Since the critically stressed zone propagates to the depth from the surface, intense anthropogenic impact on it from the surface can cause an intense earthquake with a hypocentre at a great depth.

Under such conditions where the size of rockburst and induced earthquake focus reaches hundreds of meters or several kilometers, the preparation zone covers many kilometres and is commensurable with the crustal blocks and exceeds the zone of induced impact of mining excavations. Hence, displacements along major faults are realized as part of the tectonic process, i.e. the direction of displacements along these planes during strong rock bursts correlate with the regional stress field.

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