Difference in rockburst hazard in ore and coal mines

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Abstract. In the Russian mining and engineering literature, in most cases, there is no difference in the assessment of the rockburst hazards in metal and coal mines. Nevertheless, it exists, in view of the difference in geological and geotechnical conditions of coal and ore deposits. Since ore deposits occur in the solid magmatic or metamorphic rock masses, the strongest induced earthquakes are much more powerful in ore mines than in coal mines. The main difference of rockbursting lies in the difference of natural stress state: gravity stress state in the coal fields and gravity-and-tectonic stress state in ore mines. The actual stresses are mostly vertical in the first case and horizontal in the second case, which conditions the difference in rockburst hazard in coal and ore mines.

The Russian mining and engineering literature and regulation standards are somewhat conservative in rockburst-hazard estimation in ore mines, which is connected with the history of the phenomenon. The first rockbursts in Russia were recorded in the 1940s in coal mines. Scientific men, mostly from the VNIMI Institute (S.G. Avershin, I.M. Petukhov and others) solved the problem to a certain degree and developed mine safety rules under conditions of rockburst hazard, and risk of rockbursts in coal mines was abated.

Rock bursts in ore mines in Russia started later, in the 1960s. The theoretical framework of rockburst prediction and prevention, earlier developed for coal mines, were extended to ore mines, which is wrong as geological conditions of coal and ore mines differ considerably. Some of those rules have still been in use unreasonably in the regulatory documents provided by the Federal Environmental, Industrial and Nuclear Supervision Service of Russia [1].

Ore deposits occur in magmatic and metamorphic host rocks, and both the ore and rocks possess high strength properties and deformation characteristics. Coal deposits occur in sedimentary rocks, and their characteristics are much lower. Table 1 describes strength of rock mass of some most rockburst-hazardous coal and ore deposits in Russia.

It follows from Table 1 that enclosing rock mass of ore deposits has strength by an order of magnitude higher than host rock mass of coal deposits. The stronger rock mass feature increased tectonic stresses, as shown in [3], i.e. strong rock masses are saturated with much energy. This means that the energy of the strongest seismic events in ore mines should be higher than in coal mines, and this fact is proved by practice. Table 2 compiles data on the strongest induced bursts (induced earthquakes) in ore and coal mines in Russia [4–6].

Evidently, power (energy) expressed in terms of magnitude of the strongest induced earthquakes is one–two orders of magnitude (by tens–hundreds times) higher in ore mines than in coal mines, which proves the above statement on higher energy level at ore deposits. At the same, after having analyzed the study [6], this inference is not evident. The matter is that the author of [6] made some geomechanical faults. In many cases, the author omits the scale on which the magnitude of an event
was determined. Moreover, in the reference seismic catalogs, the magnitude $m_b$ of earthquakes is determined by the teleseismic records of $P$ wave [7] hundreds and thousands kilometers away from the earthquake hypocenter. In geomechanics the local magnitude scale $M_L$ (by Richter) is used, and this scale is only applicable at the distances to 600 km from the earthquake hypocenter [7]. The most erroneous values by the $P$ wave records are given by the earthquake depth. Thus, the study [6] presents mainly incorrect, higher values of magnitudes of seismic events than, for instance, in [4] where the values of the magnitudes $M_L$ of induced earthquakes in mines are checked with respect to a number of sources. Anyway, the presented examples show that the energy of seismic events in ore mines (i.e. at the depth to 1 km below surface) is for a number of reasons higher than in coal mines in Russia.

**Table 1.** Strength of rock masses hosting ore and coal deposits in Russia.

| Ore deposits | Coal deposits [2] |
|--------------|-------------------|
| Deposit      | Rocks             | Density, t/m$^3$ | Compress ion strength, MPa |
| Lovozero, rare metals | Foyaite          | 2.65          | 160–243                  |
|              | Urtite            | 2.75          | 247                      |
| Khibiny, apatite | Lujavrite      | 2.6–2.96     | 187–332                  |
|              | Apatite–nephelene ore | 2.8–3.1     | 60–150                   |
|              | olite–urtite and rischorrite | 2.8–2.9 | 100–250                  |
| Tashtagol, iron ore | Magnetite (ore) | 3.3–4.9      | 120–140                  |
| North Ural, bauxite | Syenite, skarn, prophyrite | 2.6–3.2 | 50–180                   |
|              | Bauxite (ore)    | 2.7–3.2      | 32–220                   |
|              | Limestone (enclosing rocks) | 2.6–2.7 | 45–155                   |
|              | Argillite        | 2.50–2.90    | 20–70                    |
|              | Siltstone        |               |                          |
|              | Hardest coal     | ~1.3         | 30–50                    |
|              | (Kizelov basin)  |               |                          |

**Table 2.** Some of the strongest rockbursts and induced earthquakes in ore and coal mines in Russia.

| Ore deposit [4] | Coal deposit [5, 6] |
|-----------------|---------------------|
| No.             | Time and place of event | Magnitude $M_L$ | No.             | Time and place of event | Magnitude $M_L$ |
| 1               | 17 August 1999, Umbozer Mine, Lovozero rare metal deposit, Kola Peninsula | 5.1 | 1 | 28 August 1973, Lenin Mine, Kizelov Basin, Ural | 2.8±0.5 |
| 2               | 16 April 1989, Kirov Mine, Khibiny apatite deposit, Kola Peninsula | 4.3 | 2 | 16 July 20111, Pechora Coal Basin | 3.4 |

The most significant difference in the ground conditions of coal and ore deposits is the natural stress state. For coal deposits occurring in sedimentary rock mass, the characteristic stress state is of gravity nature, when maximum stresses are generated by the weight of overlying strata. For ore deposits enclosed in magmatic or metamorphic rock masses, it is typical to have mixed gravitational-and-tectonic stress state when the maximum stresses are induced by horizontal tectonic forces.
conditioned by the modern orogeny. The stresses in rock mass surrounding an underground excavation at a certain depth \( H \) below surface in case of gravitational and gravitational-and-tectonic stress state are illustrated in Figure 1.

![Figure 1. (a) Gravitational stress state; (b) gravity-and-tectonics stress state.](image)

The maximum stresses in the roof of the excavation in case of the gravitational stress state (Figure 1a) are governed by the weight of overlying strata:

\[
P = \gamma H,
\]

where \( \gamma \) — density of overburden rocks, t/m\(^3\); \( H \) — depth below surface, m.

In the gravity-and-tectonics stress state, the maximum stresses are generated by the tectonic component \( T \) (Figure 1b) which is oriented horizontally and, as practice shows, considerably exceeds \( P \) at the respective depth below surface. The value of the tectonic stresses \( T \) can only be determined by experimental measurements in rock mass. As a rule, the maximum horizontal stress in rocks under the gravity-and-tectonic stresses is 5–10 higher than the vertical stress conditioned by the overlying rock weight. As a consequence, rockburst hazard at ore deposits is generally governed by the tectonic stresses. Table 3 gives the characteristic of the gravity-and-tectonic stress state assessed at the most rockburst-hazardous ore deposits in Russia [8].

| Ore deposit                  | Maximum horizontal compressive stress, MPa | Ratio of vertical stress to the maximum horizontal stress in rock mass |
|------------------------------|--------------------------------------------|-----------------------------------------------------------------------|
| Khibiny (Kirov Mine)         | 20–80                                      | 1 : 3–20                                                              |
| Lovozero                     | 40–70                                      | 1 : 5–10                                                              |
| North Ural (bauxite mines)   | 25–50                                      | 1 : 2–2.5                                                             |
| Tashtagol                    | 60–90                                      | 1 : 2–5                                                               |

It is evident from Table 3 that the most rockburst-hazardous ore deposits in Russia experience sharply nonuniform stress state generated by gravity and tectonics, where the vertical stress is the lowest value. Taking into account that the compression strength at the deposits listed in Table 3 is usually \( \sigma_c = (50–200) \) MPa and in many cases is close to 100 MPa and the minimum coefficient of tectonic stress concentration in the roof and floor in mines is \( k = 2–3 \), it becomes clear that in the adjacent rock mass, the rockbursting condition is fulfilled [8]:

\[
\sigma_z \geq 0.8 \sigma_c,
\]
where \( \sigma_a \) — maximum actual stresses at the mine boundary; \( \sigma_c \) — compression strength of rock mass.

In this manner, it is natural that the tectonic stresses are the main cause of rockbursts at the listed deposits. The tectonic forces generate such stress level in rocks surrounding a mine that could be induced by the gravity forces at a depth of 2–3 km below surface.

So, the main different between natural stress states at coal and ore deposits is the vertical direction of the maximum stress at the coal deposits (Figure 1a) and the horizontal direction of the maximum stress at the ore deposits (Figure 1b). This factor has many implications. First of all, there is no notion of critical depth in terms of rockburst hazard at ore deposits. The critical depth is any mining depth at which:

\[
\sigma_{cr} > 0.5,
\]

(3)

where \( \sigma_{cr} \) — stresses causing dynamic events of rock pressure.

Under gravitation stress state, the critical stresses are readily calculated from:

\[
P = \sigma_{cr} = 0.5.
\]

(4)

There is no critical depth under the gravitational-and-tectonic stress state as the level of the critical stress is not defined by the depth but by the value of the tectonic forces. The tectonic forces in the horizontal plane have a definite orientation and to a certain degree are independent of depth. The critical stresses in rocks around an underground excavation are not conditioned by depth but depend on the direction of the excavation relative to the line of the tectonic forces. Figure 2 shows the location of epicenters of strong seismic events (\( M_L > 1 \)) in plan view of mining operations (with the horizontal lines of the daylight surface) in the west wing of Karnasurt Mine at Lovozero rare metal deposit. As seen in Figure 2, the earthquakes take places at the depths from 50 to 600 m below surface, i.e. they are independent of depth. Some of the earthquakes in Karnasurt Mine are described in [9].

Figure 2. Mining plan for the west wing of Karnasurt Mine with the surface horizontals and locations of epicenters of induced earthquakes (M—magnitude; 27.06.2016—date as dd.mm.yr).

Under the gravitational-and tectonic stress state, there are no such notions as the zone of abutment pressure, the zone of stress relief, the protecting ore body (or layer) and some other provisions.
borrowed from the coal mining practice. These notions have been formulated for the conditions of the vertical gravitational forces that govern the rockburst hazard in coal mines and mechanically adopted in the ore mining regulations [1].

The stress state of rocks mass during mining in protective ore bodies under the gravitational-and-tectonic stress state is analyzed in [10]. It is found that under dominant horizontal stresses, mining with 'protecting bodies' does not reduce rockburst hazard in rocks but generates, vice versa, conditions for the initiation of the strongest geodynamic events. At the same, the discussed notions remain actual in coal mining under conditions of the natural gravitation stress state. The orientation of the maximum stresses in rock mass is the basic difference in rockburst hazard events in ore and coal mines.

Conclusions

1. The induced earthquakes are much stronger in ore mines than in coal mines because of the higher strength of ore-enclosing rock mass of magmatic or metamorphic nature than the strength of coal-hosting sedimentary rocks.

2. Coal deposits occur in rock masses mostly subjected to gravitational natural stress state when the maximum stresses governed by the weight of the overlying rocks act in the vertical plane. Ore deposits generally experience gravitational-and-tectonic stress state when major principal stresses are generated by the tectonic forces and are oriented horizontally. This is the key difference in the rockburst hazard events in coal and ore mines.

3. Some notions mechanically taken from the rockburst-hazardous coal mining practice and adopted in the guidelines for the rockburst-hazardous or mining should be withdrawn.

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