

Rock mass diagnostics based on microseismic monitoring data at Sheregesh deposit

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Abstract. Distribution of seismic events in rocks mass around a mineral deposit is studied, it is found that the distribution features conform with the local blasting operations and geology. Epicenters of concentration zones of seismic events are detected in the area of stoping and faulting between two ore locuses. Weakening planes generated under four chronologically ordered shocks are indentified. Occurrence of these planes is characterized, and the stress redistribution after blasting is analyzed. The authors apply an integrated approach to rockburst hazard prediction, including calculus of apparent velocity of migration of seismic events during the first ten minutes after a blast and the rockburst probability assessment.

Sheregesh iron ore mining with underground method is carried out in difficult ground conditions, with exfoliation, balmstones (overhanging ledges), spalling, shocks and micro rock bursts. Major dynamic events due to rock pressure take place in the influence zone of stoping, nearby large faults and blasting sites in production ore blocks. This is for the first turn associated with the concentration of stresses in stopes, gangue pillars and enclosing rock mass. The phenomenon is aggravated under seismic effect of blasting when nonuniform loading of faults and other areas of structural weakening results in displacement of rocks along block boundaries and initiates dynamic events.

Sheregesh iron ore field is rockburst-hazardous [1]. In accord with the Federal Norms and Rules of Industrial Safety *Regulations on Safe Mining at Rockburst-Hazardous Deposits* [2] and the related *Guidelines* [1], general assessment of the deposit uses the regional prediction methods, and rockburst hazard estimation in specific areas involves the local prediction techniques. Microseismicity observation station in Sheregesh Mine of the Gornaya Shoria Division of EVRAZRUDA is one of the regional methods of stress–strain state prediction in Sheregesh ore field. On the other hand, that seismic station only performs recording of seismic events, with the definition of date, time, location and energy. Stress state prediction is neglected.

In recent years, the Siberian State Industrial University and the Novokuznetsk Institute–Division of the Kemerovo State University jointly with Sheregesh and Tashtagol Mines accomplish research work aimed to develop procedure for assessment and prediction of rockburst hazard based on the data of microseismicity monitoring [3–6]. This paper gives generalized features of seismic events occurred in New Sheregesh and Understream orebodies of Sheregesh Mine in 2014–2016, based on which rockburst hazard of these areas in the course of mining is assessed and predicted. The urgency of the prediction is caused by the increase in number of bumps and low-frequency seismic events in the



Understream orebody late in 2015–early in 2016 as compared with 2014: the effect of these events has been felt underground and by the residents of Sheregesh settlement on the ground surface. That situation complicates mining and heightens social strain.

New Sheregesh and Understream orebodies are under high-rate mining: 90% of stoping operations are carried out there. Furthermore, the orebodies are developed using concurrently two mining methods: room-and-pillar and sublevel caving with self-propelled machinery. In the long view, it is planned to change completely to the sublevel caving: major ore reserves will be extracted with this mining method in 2016.

In 2014–2016 stress state of the local ore field was generated under the influence of large-scale production blasting (LPB) in blocks 7–9 in Understream orebody and blocks 300, 24 and 25 in New Sheregesh orebody. Preparation of ore blocks for caving used process blasting (PB). Sublevel caving operation in these orebodies also used PB.

The analyses of seismic events in the Sheregesh Mine field in 2014–2016 revealed distribution of the events in conformity with the blasting operations and geology of the area.

A geological feature of Sheregesh ore field is its enclosing rock mass that is composed of rocks (skarn, diorite, porphyrite and other) that have strength and elasticity higher than ore by 1.5 times, though the ore is also rather strong. This geological feature is of concern in the assessment of conditions and behavior of probable dynamic events due to rock pressure. Another difficulty is presented by blind occurrence of New Sheregesh and Understream orebodies.

Structural geology is also of importance. Exploration and geodynamic zoning detected a fault between New Sheregesh and Understream orebodies. The fault is located based on traces of fill of a thick apophyse of syenites, along the contacts and in the middle of which zones of crush strike north-eastwards (50–60°) with a steep north-westward dip (670–85°). The fault zone is 15 m wide, the zone of jointing (influence zone) has a width of 60–140 m. The dislocation is an oblique-slip fault caused by tension and compression. Along this zone, Understream orebody is displaced north-eastward by 45–55°. The fault zone features violent jointing, the high-angle cleavage cracks have north-eastward and north-westward orientations.

The assessment of rockburst hazard in Sheregesh ore field used three criteria: distribution of epicenters of seismic events in rocks, apparent velocity of seismic events within the first 10 minutes after a PB and rockburst probability.

The criterion of distribution of epicenters of seismic events allows identifying rockburst-safe and rockburst-hazardous ore blocks. The former occur in the zone of concentration of seismic event epicenters (CSE), and the latter lie in the zones of structural blocks and potential energy concentration.

The rockburst hazard criterion based on apparent velocity of seismic events is the velocity 10^3 mm/s [7]. When the maximum apparent velocity of seismic events immediately after PB in an ore block exceeds 10^3 mm/s, the surrounding rock mass shows dynamic response to the blast. In case that this velocity noticeably grows on approach of LPB, rock mass releases some potential energy and rockburst hazard gradually lowers.

A rockburst probability p —the main index of rockburst hazard—is given by [5]

$$p = (N - n) / N ,$$

where N is the number of seismic event recorded in a 500-m zone around an ore block up to LPB, starting from blocks extracted earlier or concurrently with this block in the same area; n is the number of seismic event recorded in a 100-m zone around the block during PB on the current level and below.

When p is under 0.9, the ore block and surrounding rock mass are rockburst-unhazardous.

Based on the distribution of epicenters of seismic events (see Figure 1), the authors defined the activity of the fault between New Sheregesh and Understream orebodies (dash-and-dot line in Figure), where CSE zone was observed in 20142016. The distribution of seismic events characterizes dynamic formation of weakened planes and shearing [8].

Figure 2 shows a weakened plane governed by two angles [9]: a dip angle δ between the fault plane and the horizontal plane (x, y) and a strike angle θ set off clockwise from the x -axis (oriented toward

the North) until the extended line of intersection of the weakened and horizontal planes. This criterion allows finding the direction of flow and accumulation of tectonic energy.

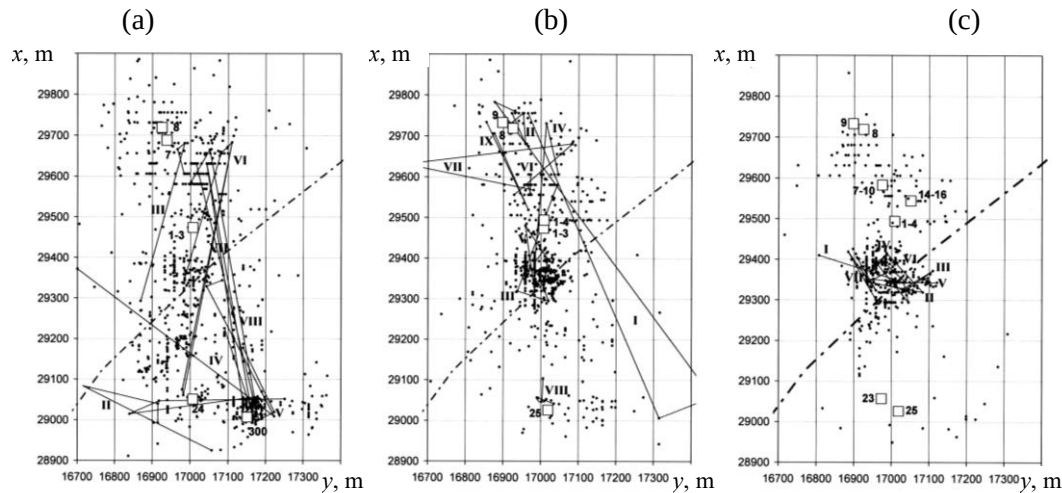


Figure 1. Distribution of seismic events in Understream orebody (above the dash-and-dot line) and New Sheregesh orebody (under the dash-and-dot line) in (a) 2014, (b) 2015 and (c) February 2016 with traces of weakened planes (solid lines): points—epicenters of seismic events; squares—centers of blocks under mining; dash-and-dot line—fault; Arabic figures—numbers of blocks; Roman figures—numbers of weakened planes.

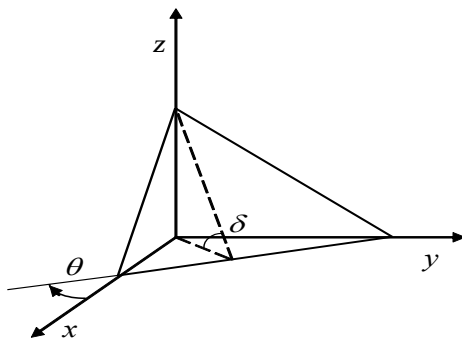


Figure 2. Elements of occurrence of a weakened plane.

Figure 1 shows the traces of the weakened planes in the form of seismic events and lines chronologically connecting them. In New Sheregesh and Understream orebodies, 8 and 9 weakened planes appeared in 2014 and 2015, respectively (see Table 1); these planes are activated by the process and production blasting.

It is noteworthy that CSE zone was generated near block 300 in 2014 (Figure 1a), and in 2015 and 2016 such zones were initiated in the area of the fault (Figures 1b and 1c). Rock mass in CSE zones contains many weakened planes and is incapable to accumulate potential energy. The weakened planes generated by mining in blocks 300, 1–3–120 and 1–4–164 in 2014 were reflective of stress redistribution between New Sheregesh and Understream orebodies and the fault. Planes I, V and VII were the channels for the tectonic energy to flow from CSE zone to periphery of New Sheregesh and Understream orebodies. Planes II, II and IV were the channels for the energy to flow from the fault inside New Sheregesh (planes II and IV) and Understream orebody (plane III). The longest planes appeared between the orebodies after LPB in block 300 and PB in blocks 1–4–20 and 1–3–164.

Table 1. Conditions and parameters of weakened planes in Sheregesh and Understream orebodies in 2014–2015.

Plane no.	Date (dd.mm.yy)	Time (h:min:s)	Operation	Dip, deg	Strike deg
2014					
I	01.02.2014	20:03:53	31.01.2014—PB, explosive 9.0 t, block 300	49	106
II	04.02.2014	12:03:04		8	118
III	11.02.2014	17:33:18		50	167
IV	11.05.2014	16:22:18	26.04.2014—PB, explosive 8.6 t, block 300	7	106
V	23.05.2014	16:52:17	21.05.2014—PB, explosive 0.8 t, block 50	28	173
VI	25.10.2014	11:49:15	25.10.2014—PB, explosive 7/2 t, blocks 1–4–120	58	172
VII	07.12.2014	21:23:31	07.12.2014—LPB, explosive 257.8 t, block 300	71	10
VIII	29.12.2014	20:24:22	28.12.2014—PB, explosive 12.0 t, block 1–3–164	29	27
2015					
I	18.01.2015	09:03:57	18.01.2015—LPB, explosive 139.0 t, block 8	15	24
II	18.01.2015	09:14:45		50	176
III	20.01.2015	10:48:02	25.01.2015—PB, explosive 2.1 t, block 1–3–164, PB, explosive 12.2 t, block 7	25	77
IV	27.01.2015	01:54:40		67	176
V	28.01.2015	10:07:16	12.06.2015—LPB explosive 110.0 t, block 8	6	115
VI	12.06.2015	09:40:32	16.08.2015—LPB, explosive 61.1 t, block 25	79	14
VII	13.06.2015	11:22:34		22	62
VIII	16.08.2015	08:06:59	12.09.2015—LPB, explosive 52.0 t, block 9	26	65
IX	12.09.2015	08:24:45		58	172

In 2015 during mining in block 87, five weakened planes were found to intersect the block and CSE zone in enclosing rock mass. The planes had mostly north-westward and northward strike. The longest plane ran across both New Sheregesh and Understream orebodies. The other planes were mostly located in Understream orebody, between the fault and the actual stoping zone. These planes were the tectonic energy flow channels from CSE zone to the periphery of Understream orebody. It is noteworthy that major energy flew to the north-west of the orebody, in blocks 7, 8 and 9. That was probably connected with the tectonic stress field assessed by VostNIGRI [10]: $\sigma_1 = 2.6\sigma_3$; $\sigma_2 = 1.4\sigma_3$; $\sigma_3 = \gamma H$. The azimuth of the major stress σ_1 outside the influence zone of stoping, $A\sigma_1 = 335^\circ \pm 15^\circ$, was oriented northwestward in line of the orebody strike.

To correlate seismic events in 2014–2016 and blasting, Figure 3 shows the number of low-frequency events and bumps as against explosive weight in LPB and PB. It is clearly seen in the figure that the majority of bumps and low-frequency events took place after PB in block 8 (stages 1 and 2) and in block 9 (stages 3 and 4) on Level (+185) – (+255) m and after PB in blocks 4–1–164 and 7–10–164 on Level (+115) – (+185) m. The maximum number of bumps (184) and low-frequency events (1124) was recorded after PB in block 7–10–164 on February 25, 2016. The increase in the number of low-frequency events, especially in February 2016, is indicative of formation of a natural equilibrium arch in rock mass above the mined-out cavity in Understream orebody, which weakens the overlying strata and can induce movement in them up to the ground surface.

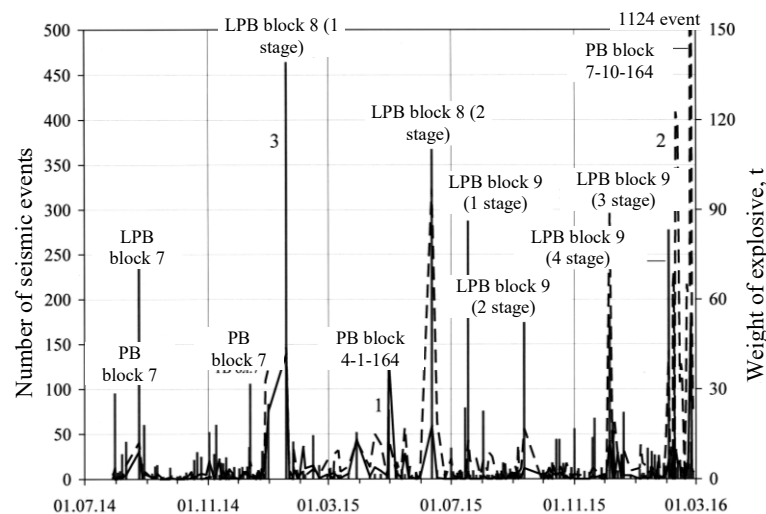


Figure 3. Time history of seismic events after blasting in Understream orebody: 1—bumps; 2—low-frequency seismic events; 3—quantity of explosive.

High activity of rock mass can result from simultaneous different-scale blasting in a confined environment of blind orebodies with large mined-out voids. Stress state of rocks mass around Understream orebody in 2015–2016 was generated by 6 large-scale blasts (2 LPB in block 8 and 4 LPB in block 9).

The increased rockburst hazard near blocks 7, 8 and in Understream orebody was observed since 2014, after large-scale blasting in block 7 when rockburst probability exceeded the allowable value of 0.9 and equaled 0.935. Also in 2014, the recorded apparent velocity of seismic events was 162 mm/s at the criteria value of 1000 mm/s. The maximum rockburst probability was assessed after two stages of LP in block 9—0.937. By the end of 2015, this value reduced to 0.933. After the third-stage LPB in block 9 (December 6, 2015), the maximum apparent velocity of seismic events considerably grew from 224 mm/s (during 9 months of 2015) to 22909 mm/s (at the end of 2015). So, surrounding rock mass of block 9 dynamically responded to LPB and released accumulated potential energy, and rockburst hazard began lowering.

In the area of mining with a new technology and self-propelled machinery in Understream orebody, the rockburst probability was 0.871 late in 2015, which was lower than 0.9 but higher than in the course of previous 9 months of 2015 by 0.025. Although the insignificant increase in the rockburst hazard probability and the absence of seismic events within 10 min after PB, the situation meant higher rockburst hazard in the vicinity of sublevel caving area in the orebody.

On that background, LPB with 83 t of explosive was performed in block 9 (stage 4) on February 3, 2016 and PB with 12 t of explosive was carried out in block 7–10–164 on February 25, 2016, which critically increased the number of low-frequency seismic events and bumps in the enclosing rock mass. The bumps after that PB and until the next day PB in block 5–8–142 took place mostly in the influence zone of the fault between New Sheregesh and Understream orebodies. Seismic energy of the blasts activated numerous dislocations (weakened planes) governing the fault (see Figure 1c). Shearing started on those planes and induced various energy bumps. The planes were steeply dipping and shears occurred one after the other (Table 2). Apparently, shear along one plane activated shear along the next plane as in “domino”, and the trigger was seismic energy of PB in block 7–10–164 200 m northward of the fault. The similar situation took place after each PB, while tens PB were executed each month plus 6 LPB in 2015–2016. Mostly bumps located in CSE zone around the fault that was a sink of energy of all LP and PB in New Sheregesh and Understream orebodies.

Thus, based on the stress assessment in rock mass around New Sheregesh and Understream orebodies, rockburst-hazardous zones were identified, which enabled resuming mining operations with the social tension removed.

Table 2. Weakened planes around the fault between New Sheregesh and Understream orebodies.

Weakened plane	Date (dd.mm.yy)	Time (h:min:s)	Bump energy class	Dip, deg	Strike, deg
I	25.02.2016	07:48:28	3.6	31	58
II	25.02.2016	08:42:41	3.6	4	51
III	25.02.2016	09:43:34	1.8	50	119
IV	25.02.2016	12:22:32	2.2	87	140
V	25.02.2016	12:50:27	2.7	77	87
VI	25.02.2016	15:09:07	1.3	65	99
VII	25.02.2016	16:12:10	1.7	79	40

Conclusion

It has been found that distribution of seismic events and generation of weakened planes activated by process and production blasting assists in determination of flow and accumulation of tectonic energy.

The causes of activation of seismic events (bumps and low-frequency events) after blasting are revealed.

The authors have illustrated feasibility of rockburst hazard assessment and prediction based on integrated application of three rockburst hazard criteria: distribution of epicenters of seismic events, apparent velocity of seismic events during the first 10 min after a process blast and rockburst probability.

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